TREE-CROP COMPATIBILITY IN AGROFORESTRY: PRODUCTION AND QUALITY OF COFFEE GROWN UNDER MANAGED TREE SHADE IN COSTA RICA

By

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Dedicated to my family in Germany and Haiti.

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Abstract of Dissertation Presented to the Graduate School of the University of Florida in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy

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By

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While trees are claimed an essential component of many traditional low-input land-use systems, they are increasingly eliminated from modern high-input systems to avoid competition for water, nutrients, and light. Reports about shade effects on coffee production are contradictory, probably due to differences in biophysical environments, plant materials, evaluation criteria, and timeframes of the studies. This study was motivated by the hypothesis that the benefits of shade increase with biophysical limitations on coffee production.

The objectives of the study were to

1. evaluate the effects of shade on vigor, production, and quality of commercially grown coffee under low-elevation high-humidity, i.e., ecologically suboptimal, conditions for coffee, and

2. compare tree species with regard to their compatibility with coffee.

The study showed that coffee plants under intermediate homogeneous shade (30% to 50% PAR) by *Erythrina poeppigiana* produced equally well as those grown without shade but had healthier fruits and were more vigorous. Shading above 80% reduced production by 37% for *Coffea arabica* var. Caturra but only by 12% for var. Catimor. Permanent shade suppressed weeds strongly. No shade and pollarded tree shade increased the incidence of the fungal pathogen *Cercospora coffeicola*. The incidence of *Hemileia vastatrix* and *Mycena citricolor* did not differ among treatments.

Shade increased fruit weight and bean size, more for Catimor than for Caturra, without affecting the conversion rates from fruits to green coffee. A tasting experiment demonstrated, for both varieties, shade-induced improvement in appearance of green and roasted coffee as well as in acidity and body of the brew. Aroma of Catimor was affected adversely by shade.

Correlations between distance to the nearest tree and flowering, production, vigor, and health of coffee plants

suggested high compatibility between coffee and individual trees of *Cassia grandis*, *Casuarina equisetifolia*, and *Eucalyptus deglupta* under conditions without water limitations. In contrast, *Croton killipianus* and *Citrus aurantium* affected coffee adversely. The transect-based methodology used may help to rapidly screen tree species for their compatibility with coffee. The beneficial effects of shade on coffee production, vigor, and bean quality illustrate the trees' facilitative effects, especially pronounced under ecologically suboptimal conditions common to many coffee regions.

CHAPTER 1
GENERAL INTRODUCTION

Among the options for sustainable land-use practices discussed in global fora, agroforestry is often seen as one, if not the most, promising candidate (Nair 1993; CATIE 1994). Worldwide, increasing demands for tree products and their environmental services have made the scientific study of agroforestry a high priority (Nair 1993; CATIE 1994; Muschler and Bonnemann 1997). In Latin America, one of the most important crops in agroforestry systems is coffee (*Coffea arabica* L.)(Budowski 1987; Beer et al. 1998).

Coffee and Trees

Importance of Coffee

From 1992 to 1997, Latin America contributed between 61% and 71% of the annual world coffee production which reached close to 100 million 60-kg bags of raw coffee in 1996/97 (Camacho et al. 1997; FAO 1995). At prices FOB ("freight-on-board"), this generated US$ 8.7 billion for the Latin American producers in the coffee year 1994/95 (Jiménez Castro 1997). For many countries of Latin America coffee has been, and continues to be, one of the main sources of

foreign exchange (Hall 1976; Wrigley 1988; Jiménez Castro 1997).

With its annual production between 2.3 million and 3 million 60-kg bags for the period 1992 to 1997, equivalent to roughly 3% of global coffee production, Costa Rica is among the top twelve coffee producers in the world (Camacho et al. 1997; FAO 1995). Revenue and employment generated by coffee remains of crucial importance: between 1992 and 1996, coffee production generated annually between 200 million and 420 million US$ and employed about 23% of the agricultural workforce of Costa Rica (Camacho et al. 1997). World-wide, Costa Rica has one of the highest per hectare productivities of coffee (FAO 1995), in large part due to excellent biophysical conditions caracterized by ideal climate and deep volcanic soils in the main coffee areas of the "Central Valley", and by intensive use of agrochemicals.

Besides its direct economic impact, coffee cultivation also has strong ecological effects with consequent economic implications (Huston, 1993). These effects result primarily from the impacts of cultivation practices on soil fertility and soil health (Rice 1991; Fassbender 1993; Doran et al. 1996), environmental contamination (Boyce et al. 1994), and biodiversity (Schulze and Mooney 1994; Wille 1994; Perfecto et al. 1996; Greenberg et al. 1997). Due to the longevity of

individual coffee plants on the order of 20 to 50 years, depending on variety and agroecological conditions, these ecological impacts tend to be long-term (Wrigley 1988; Boyce et al. 1994).

There are two main systems of producing coffee: first, the high-input and, typically, large-scale and capital-intensive coffee monocultures, and second, the more traditional, low- or moderate-input systems which usually have more or less intensely managed trees associated with coffee (Hall 1976; Fernandez and Muschler 1998). Despite the active promotion of high-input systems during the past five decades, typically accompanied by reduction or elimination of trees in coffee fields, growing coffee in association with shade trees remains one of the most widespread agroforestry systems in Central America (Beer et al. 1997, 1998; Echeverri et al. 1997; Muschler and Bonnemann 1997).

Importance of Trees

Many studies have focused on different aspects and functions of trees in coffee systems. Examples are system descriptions from Mexico (Jimenez 1979; Fuentes 1979; Jimenez and Gomez-Pompa 1982), Costa Rica (Espinoza 1985) and Venezuela (Escalante 1985; Herrera et al. 1987), evaluations of litter production, nutrient cycling and N_2-fixation (Jimenez and Martinez 1979; Aranguren et al. 1982;

Bornemisza 1982; Lindblad and Russo 1986; Beer 1988; Nygren 1995), timber production (Somarriba and Beer 1987), coffee yield under different shade tree densities (Detlefsen Rivera 1988; Beer 1992), coffee yield as a function of fertilization with and without shade (ICAFE-MAG 1989; Ramirez 1993; ICAFE 1996b; Ramirez 1997), or overall economic revenue (e.g., Barker 1991; Chamorro et al. 1994). However, while these investigations provide important details on their respective foci, they often cannot explain seemingly contradictory effects of a particular tree species or why factors such as shade that limit production on one site may increase production on another. Such questions can only be answered by information about the factors that limit production along environmental gradients of, above all, elevation, moisture and cloudcover, nutrient availability, and external inputs. Unfortunately, this kind of information along resource gradients is still very fragmentary (Casper and Jackson 1997).

Recent years have seen an increasing interest in many Latin American countries to implement new coffee-production systems or improve existing ones with associated trees, among them high-value timber species (cf. country reports in Echeverri et al. 1997; Galloway and Beer 1997; Muschler 1998). Under optimum or close-to-optimum conditions for

coffee growth, intensive management has often resulted in mono-specific shade of intensely pruned trees or unshaded plantations. According to Carvajal (1984), such optimum conditions include deep fertile soils, mean annual temperatures between 17°C and 23°C, a mean annual rainfall of 1600 mm to 1800 mm, a marked dry season of less than three months duration, and absence of strong winds.

Under conditions differing from these, from hereon referred to as suboptimal conditions, the shade tree density and diversity are often higher (Rodriguez 1935; Beer 1987a). For example, in the areas of Acosta and Puriscal in Costa Rica, dominated by low-fertility soils on steep slopes, Espinoza (1985) listed over 60 different shade tree species used, most in small farms of less than 1 ha. The most common were the fruit trees *Citrus* spp., *Persea americana,* and *Musa* spp., the legumes *Diphysa robinioides*, *Inga* spp., and *Erythrina spp.,* and the timber species *Cedrela odorata* and *Cordia alliodora*. Many of these species are also common in coffee farms on the Atlantic side of Costa Rica that are also subject to suboptimal conditions for *Coffea arabica* due to high temperatures at low elevations, lack of a marked dry season (see Chapter 2), and often, as in Turrialba, highly acid soils on steep slopes (Kass et al. 1995).

These systems with shade trees are often referred to as "traditional" systems in contrast to the "modern" systems of growing coffee without shade or with trees that are pruned so intensely that shade is virtually eliminated. The "modern" systems usually require more capital to purchase chemical inputs (Machado 1959; Wrigley 1988; cf. discussion of costs in Chapter 3). In order to avoid such expenses, many coffee farmers retain shade trees for their production of fruits or wood and, in some cases, for their beneficial effects on the microclimate (Barradas and Fanjul 1986), on soil fertility, or other factors that may help to facilitate growth of the associated crops (Callaway 1995). The products obtained from the shade trees (fruits, timber, fuelwood, fodder) help to compensate for the unstable and often low prices of coffee on the world market (Beer et al. 1998). However, the importance of trees may also increase in optimum coffee environments if coffee prices remain low or decline, a likely scenario according to the International Coffee Organization (Seudieu 1997). This would force farmers, even in optimum ecological environments for coffee, to diversify or modify their production, following similar pressures as in the early 1970s in Costa Rica as a response to low coffee prices (BCCR 1973). One way would be by integrating trees and their positive effects into their

coffee plots. However, these positive effects of trees need to be balanced against their drawbacks.

The main drawbacks of trees in coffee plantations stem from the potential negative effects on the coffee plants, primarily through excessive shading, competition for water and nutrients, allelopathy, or possible favoring of fungal infections of the coffee plants (Beer 1987a and b; Muschler 1993; Beer et al. 1998; Table 1-1). Among the many roles of trees, shading may be one of the most crucial due to its multiple direct and indirect effects on microclimate (Barradas and Fanjul 1986; Monteith et al. 1991) and coffee physiology (Fournier 1988; Nunes et al. 1993).

The Sun-Shade Controversy

The discussion on whether or not the best cultivation practice should include trees or not has been on-going ever since coffee was introduced to Latin America in the early 18th century (Lock 1888; Cook 1901; Alvarado 1935; Montealegre 1954; Guiscafre-Arrillaga 1957; Fournier 1988; Muschler 1997a). The development and increasing use of agrochemicals during the past fifty years favoring the elimination of trees on the one hand, and recent concerns about environmental sustainability calling for more trees on the other, have stimulated this discussion (Wrigley 1988; Rice 1991; Smith et al. 1992; Boyce et al. 1994; Fernandez

Table 1-1. Documented benefits and costs of growing coffee with shade trees in Central America.

BENEFITS:

- moderation of microclimate (reduced heat load and transpiration).
- reduction of input and labor requirements (fertilizer, herbicides).
- production of mulch, fruits, and wood.
- contribution to maintenance of soil fertility.
- reduction of "Brown eye spot" (*Cercospora coffeicola*).
- improvement of coffee quality.
- extension of productive life of coffee.

COSTS:

- reduction of coffee yield (site-dependent).
- requirement of additional labor for maintenance/pruning of trees.
- enhanced risk of fungal diseases, esp. "South American Leaf Spot" (*Mycena citricolor*); effects on "Coffee Leaf Rust" (*Hemileia vastatrix*) are controversial.

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and Muschler 1998; Gliessman 1998). While particularly largescale coffee producers with sufficient financial resources were able to increase coffee production by replacing shade trees with chemical inputs, albeit often not long-term due to reduced soil fertility (Boyce et al. 1994), this change in production method generally excluded smallscale and resource-limited farmers. This latter group, representing the majority of coffee producers world-wide (Hall 1976; Ridler 1982), continue managing trees in their coffee fields. As a result, today coffee is produced in both systems and the sun vs. shade controversy carries on with each party claiming to have the better system. A brief review of the ecophysiology of coffee helps to focus on the issue.

Ecophysiology of Coffee

Research on coffee systems is as old as coffee cultivation, and detailed written reports about coffee responses to different environments date back more than a century. In a 19th century account of coffee cultivation systems in Ceylon (today Sri Lanka), then one of the largest producers, Lock (1888) described many reasons for reduced vigor and production of coffee plantations. Among them, removal of shade and poor soil conditions were prominent. Some years later, Cook (1901) published the first detailed

account dedicated exclusively to shade and its benefits for coffee. Sources like these, and the increasing need for information to improve the management of expanding coffee estates, fueled the development of physiological and ecological research on coffee from the 1930s onward.

The following review on ecophysiology of coffee covers the main findings since then, focusing on the effects of temperature, elevation and light on coffee, the factors of primary interest to this study. Works relevant for the discussion of specific results of this study (Chapters 3, 4 and 5) are incorporated into the respective chapters and are not cited here. Complete reviews on coffee ecology and physiology can be found elsewhere (Maestri and Barros 1977; Carvajal 1984; Cannell 1985; Wrigley 1988; Barros et al. 1995; Beer et al. 1998).

Temperature and elevation

The optimum mean annual temperature (MAT) for coffee lies at 20°C with a range from 17° to 23°C (Maestri and Barros 1977). This temperature coincides with the mean annual temperature of forests in the Ethiopian highlands, where coffee evolved as an understory shrub (Sylvain 1955). According to Nunes et al. (1968), coffee is very sensitive to temperature. Highest growth rates of leaves were measured at a day/night temperature of 24°/20°C. Coffee plants

exposed to temperatures above 25°C suffered a 10% reduction of photosynthetic rate for every degree C increase. Similar results by Kumar and Tieszen (1980) confirmed the early work by Nutman (1937) who had documented mid-day stomatal closure for coffee in Kenya. Since leaf temperature can exceed air temperature substantially on sunny days by as much as 15°C for a sunlit leaf exposed to an ambient temperature of 29°C (Butler 1977), it is likely that temperature is the key factor controlling photosynthesis under such conditions. Plant growth can furthermore be limited by high soil temperatures, as shown by Franco (1958) for pot-grown plants when soil temperature exceeded 26°C, the optimum temperature for root growth.

Considering that a change in elevation of 100 m corresponds to a change in temperature of about 0.6°C (Nieuwolt 1977), the range of 4° to 6°C between the minimum and maximum mean annual temperatures for coffee cultivation is roughly equivalent to an elevational range of 700 m to 1000 m. Therefore, plants growing 350 m to 500 m below or above the environment with MAT of 20°C would be exposed to the temperature limits given by Nunes et al. (1968) and Kumar and Tieszen (1980). This illustrates the preeminent

role of temperature for coffee, both for photosynthesis as well as for elevational distribution.

Light

With few exceptions (which can be explained as artefacts or peculiar experimental conditions), physiological studies at the leaf- or plant-level have demonstrated that the maximum rates of photosynthesis or growth of *Coffea arabica* are achieved at intermediate levels of shade, typically ranging from 30% to 50% (Nutman 1937; Huxley 1967; Kumar and Tieszen 1980; Nunes et al. 1993; Fahl et al. 1994). Since the light saturation of coffee occurs at relatively low levels, around 300 μmol m^{-2} s^{-1} of PPFD (photosynthetically active photon flux density) for shade-adapted and 600 μmol m^{-2} s^{-1} PPFD for sun-adapted leaves (Kumar and Tieszen 1980; Fahl et al. 1994), full sunlight (exceeding 2000 μmol m^{-2} s^{-1} PPFD) can cause strong photoinhibition (Nunes *et al.* 1993). Although nitrogen fertilization can reduce the extent of the underlying protein damage in the photosystem II, even fertilized plants can suffer long-term damage from sudden exposure to full sun (Nunes et al. 1993).

Exposing 1.5-year-old shade-grown seedlings to full sun, Nunes *et al.* (1993) reported that, although the

surviving N-fertilized plants were able to recover their full photosynthetic rate after about two weeks, they still had only about 50% of the pre-experimental leaf area after four months. Plant mortality after four months was 30% and 100% for the fertilized and non-fertilized plants, respectively.

Undoubtedly, while this type of information is essential for understanding physiological processes at the plant or leaf level, the application of it to the plantation level is strongly limited. The limitation lies in the fact that the data were derived from individual plants or even plant parts, often evaluated under laboratory conditions for only short periods of time during juvenile growth (e.g., Tanada 1946; Huerta 1954; Nunes et al. 1968; Nunes et al. 1993; Fahl et al. 1994).

In contrast, most, if not all, of the studies published on the effects of shade at the plantation level, involving several years of coffee harvests and large environmental heterogeneity, lack adequate quantification of the shade levels used (e.g., Montealegre 1954; Suarez de Castro et al. 1961; Ramirez 1993; Aldazábal and Alarcón 1994a; Guyot et al. 1996; Ramirez 1997). This lack of information also hampers the interpretation and extrapolation of the data to other situations. For example, while (unquantified) shade

and recycled nutrients from pollarded *Erythrina poeppigiana* were found to be highly beneficial for unfertilized *Coffea arabica* in a 10-year study in Turrialba at 650 m a.s.l. (Ramirez 1993), their benefits for unfertilized coffee were much smaller, yet still marked, in an experiment conducted in the Central Valley of Costa Rica at 1375 m a.s.l. (Ramirez 1997). Given similar soils and management inputs, it is likely that other differences in the biophysical environment, particularly elevation, may have played the key role in determining the treatment responses. However, given the lack of information on the actual shade levels, it is not possible to verify the effect of potential differences in shade.

The proper interpretation of data, both at the plant-level as well as at the plantation-level, is further complicated by the large number and dynamics of other factors interacting with vegetative and reproductive growth of coffee in an agroforestry system. Being a perennial, coffee performance is also subject to a carry-over effect of interactions in the past. The following section gives a graphical presentation of a coffee system with one associated tree species. It is included to present the complexity of the main biophysical interactions in a

simplified agroforestry system such as the coffee and *Erythrina* system described in Chapters three and four.

Complexity of Coffee Agroforestry Systems

Even a simple agroforestry system such as coffee plus only one tree species, is more complex than many agricultural or forestry monocultures (Muschler 1997c). This is of great importance for assessing the potential impacts of different management options for coffee.

Using energy language, adopted from Odum (1983), to diagram a system of coffee with one tree species, the main components can be arranged into four groups (Fig 1-1): (1) Inputs and outputs crossing the system boundary: the main inputs are "natural" inputs such as sunlight, rain, and nutrients from soil formation, and "human" inputs of fertilizer, pesticides, and labor. The main outputs are nutrient and water losses from the system, and tree and coffee products exchanged in the market for money needed for the purchase of "human" inputs. (2) Production units: the main units are trees, coffee plants, and weeds. (3) Storage compartments: these include foliage of the plants, water, nutrients, wood, coffee, detritus, spores of diseases, and, ultimately, money. Finally, group (4) consists of switches and valves describing the intensity of processes such as

soil erosion, tree pruning, coffee diseases and their chemical control, and weeding operations.

The arrows in Fig 1-1 represent the interactions that link individual components. For example, coffee production is driven by the inputs sunlight, water, nutrients, and photosynthetic organs (F). Each one of these inputs depends on other compartments in the system. Thus, for example, the light available for coffee is a function of the pruning intensity of the shade tree which, simultaneously, increases the input to detritus. This, in turn, feeds into the nutrient pool and also contributes to controlling soil erosion. Depending on the fraction of coffee foliage that becomes detritus, either directly through aging, die-back or pruning, or indirectly through disease infection (determined by the number of fungal spores which, in turn, depends on the spraying intensity of fungicides), more or less coffee berries can be produced for the market. The overall vigor of the coffee plant determines its use of primary inputs and thus resource partitioning with the other components. Vigorous coffee and tree growth may trigger competition between them for nutrients and water, and the taller components will reduce the light available for the smaller plants in the system.

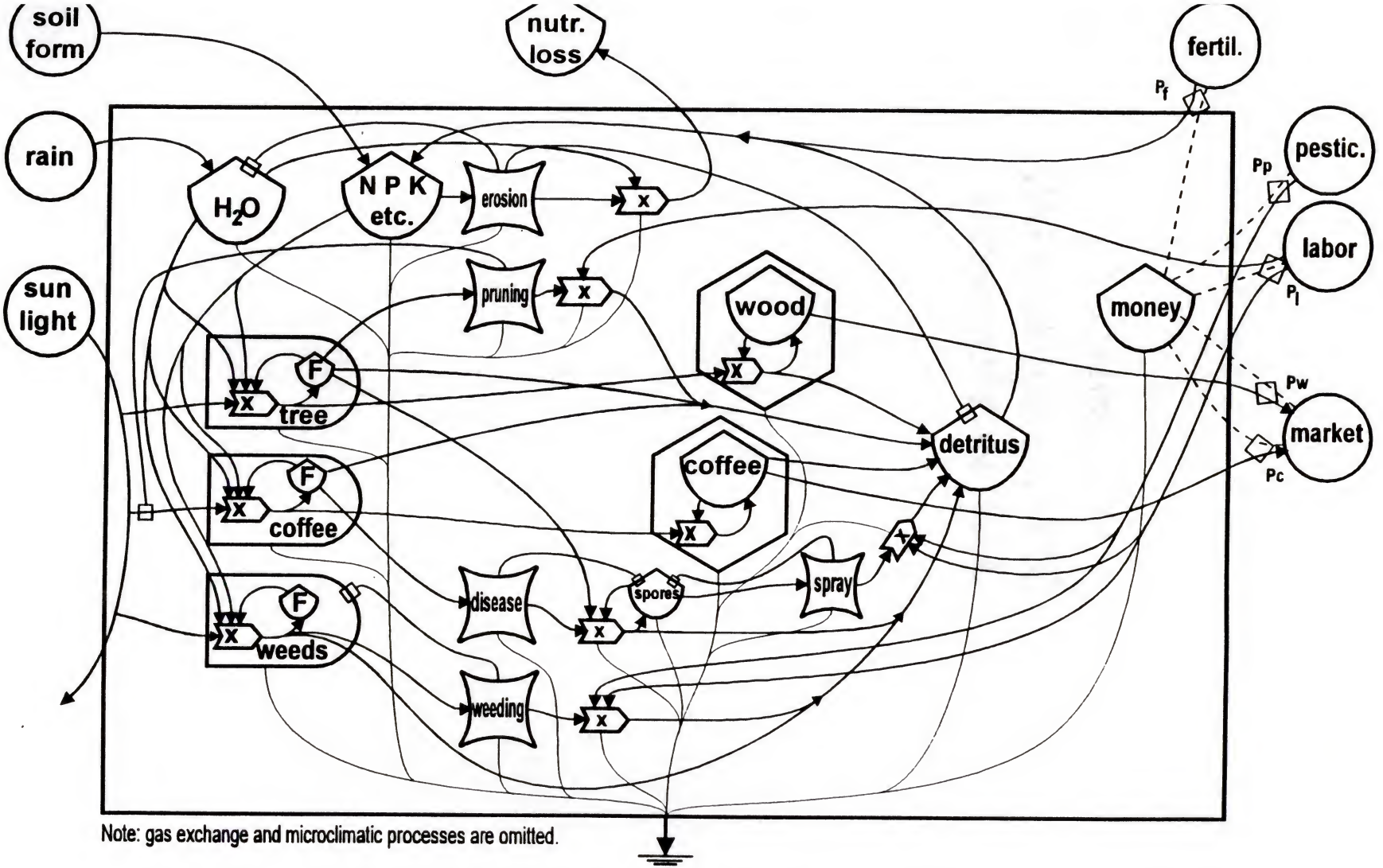

Figure 1-1. Energy diagram (sensu Odum 1983) with the main components and interactions of a shaded coffee system with one tree species. The symbols labeled "F" represent photosynthetic plant parts, and "x" stands for values that determine the flow of energy.

The large number of components and interactions between them are responsible for the high structural and functional complexity of this apparently simple system. And that despite the omission of many other elements such as the production of faunal and microbial biomass, herbivory or gas exchange, and microclimatic processes. The long life expectancy of agroforestry systems with perennial crops adds another dimension to complexity since all interactions are subject to change as trees and crops age.This complexity of the system illustrates why performance evaluations based on only one, or at best a few, input and output variables and short timescales are inadequate for supporting the claims of the sun or shade advocates. Unfortunately, the vast majority of references used for that discussion suffer from such limitations leaving many open questions despite more than a century of organized coffee research.

Open Questions

Since coffee is typically grown in humid environments with > 1200 mm rain and a relatively short dry season, often on relatively fertile volcanic soils (at least in Central America; Wrigley 1988), the effect of shading of coffee plants by tree crowns may often be more critical than that of competition for water and nutrients. Most of the still scanty information about the relative importance of above-

and belowground interactions along resource gradients suggests that belowground competition often decreases with increasing nutrient levels (Casper and Jackson 1997). For example, Putz and Canham (1992) showed that shoot competition between tree seedlings and shrubs became more important than root competition with increasing site productivity. Similarly, long-term monitoring of a coffee association with *Erythrina poeppigiana* and *Cordia alliodora* on a fertile soil at CATIE, Turrialba, Costa Rica, appears to support this hypothesis. Competition for water and nutrients seemed less important than shading under these conditions (Beer 1992).

However, systematic studies on the transmission of photosynthetically active radiation (PAR) through crowns of promising tree associates for coffee are missing. The information available is often qualitative such as "heavy shade" or "50% shade" without further specifications, and reported measurements are often not comparable due to different methodologies used.

Among the most urgent questions about shading of coffee in agroforestry associations are:

1. Under what conditions is shade beneficial?
2. How much shade (in terms of photosynthetically active radiation PAR) is best for different varieties and in what spatial and temporal distribution?

3. Which tree species provide such shading with minimum management and maximum compatibility with coffee?

4. How can this type of shading be achieved by planting these tree species in different spatial arrangements?

These questions led to the definition of the general objectives and hypotheses of the study.

Objectives and Hypotheses

Based on indications in the literature (e.g., Lock 1888; Beer 1987a; Wrigley 1988; Ramirez 1993), I hypothesized that shade trees would benefit *Coffea arabica* especially in suboptimal biophysical environments. Under such conditions of, for example, temperatures or moisture regimes outside of the optimum ranges described above, the trees would facilitate coffee growth and production through reduction of the environmental constraints, particularly heat and water stress.

The general objectives of the study were to:

1. evaluate the effects of shade on vigor, production, and quality of commercially grown coffee under low-elevation high-humidity, i.e. ecologically suboptimal, conditions for coffee, and

2. compare selected tree species with regard to their compatibility with coffee.

The study is presented in seven chapters. This introductory chapter is followed by an account of the motivations and limitations for working on-farm and the

environmental characterization of the research areas chosen (Chapter 2). Chapter 3 summarizes coffee vigor, disease, and production under different shade levels of *Erythrina poeppigiana*. In Chapter 4, I present the main effects of three shade on coffee quality. The final research chapter, Chapter 5, reports the results of a transect-based methodology to rapidly assess the tree-crop compatibility of five other tree species. Chapter 6 summarizes management recommendations for trees in coffee and presents a graphical hypothesis to predict tree effects on coffee production as a function of elevation and soil conditions. And, finally, Chapter 7 summarizes the main findings and conclusions and gives research recommendations.

CHAPTER 2
SELECTION AND CHARACTERIZATION OF THE RESEARCH PLOTS

This chapter consists of two main sections. In the first section I summarize the factors that motivated my decision to work under on-farm conditions. The second part characterizes the biophysical environment of the chosen research plots.

Assessing Coffee Performance under On-farm Conditions

Since the early 1980s the call for more direct researcher-farmer interactions, the central theme of "Farming Systems Research and Extension" and "Participatory Research", has become stronger. Examples are works on concepts and methodologies in this area compiled by Hildebrand and Poey (1985), Hildebrand (1986), Chambers et al. (1989), Mutsaers and Walker (1991), Pretty (1995), Hildebrand and Russell (1996) and CATIE (1997). Although on-station research undoubtedly has its importance for specific objectives that require high precision, most of the applied research needed today might be more effective and cost-efficient when done directly on farms (Chambers et

al. 1989; Hildebrand and Russell 1996). These considerations motivated me to conduct this study as on-farm trials in commercial coffee plantations around Turrialba, Costa Rica. This setting permitted me to reduce costs while being able to maximize contact with the farmer and to incorporate the feedback of the farmer and labor personnel into the on-going evaluations. Such immediate feedbacks are essential ingredients for successful technology generation (Chambers et al. 1989; Hildebrand et al. 1993; Hildebrand and Russell 1996; Monterrey et al. 1997). The following sections in this chapter summarize the main advantages and limitations of on-farm research in general and then present the specific implications of the on-farm decision for the selection of sites, plants, and parameters for this study.

Advantages of On-Farm Studies

The main advantages of on-farm versus on-station work may be grouped according to the four sequential stages of experimental work: (1) definition of research needs; (2) environmental and crop management; (3) data collection; and, (4) interpretation and application of new information. The adoptability of the new or improved practices is likely to be higher if the farmers' priorities and visions form the main focus during all these stages (Landeck 1991; Pretty 1995; Hildebrand and Russell 1996). In that case,

the researcher's main role is to organize these priorities and to translate them into scientifically sound studies.

On-farm work is attractive during the first two stages because it is the farmers themselves who prioritize research needs for their conditions and who, then, choose the environmental and crop management that best suits their objectives. Site preparation, plant establishment, pruning, fertilization, and control of pests and diseases are done by the farmers based on their present priorities and long-term experience, often including knowledge of several generations.

During the next stage, data collection, the advantages of on-farm work derive from the incorporation of the farmers' perspectives on what and how much of it is important. Both the focus and detail of data collection can, and should, be adjusted to the farmers' information needs. For this study, on-going discussions with the farmers formed the foundation for prioritizing the importance of the different parameters to be studied, and for adjusting the level of detail necessary to generate the information needed.

And finally, if experiments were developed on farms, it would generally be easier to transfer and apply the new information (Pretty 1995). In fact, transfer and

application of on-farm results may require only minimum efforts since the new solutions were developed to be within the farmers' capacities, and the experimental plots could continue to serve as demonstration plots. Under these circumstances, farmer-to-farmer transfer, possibly the most effective way of extension (Chambers et al. 1989; Landeck 1991), would be greatly facilitated.

In summary, working directly with farmers on their farms presents a unique opportunity to learn about the rationale of their daily decisions, an obligate prerequisite for generating information for them. Taken together, these aspects form the main underpinnings of generating relevant and adoptable information for farmers as end-users. This was the motivation for developing this research on commercial farms. However, there are also important limitations inherent in this type of work that need to be considered in order to generate scientifically sound results.

Constraints of On-Farm Studies

The main constraints of on-farm work are rooted in, first, the reduced levels of control and records of the different crop management activities carried out and, second, limitations to the detail and accuracy of measurements and monitoring. Rather than imposing a certain

quantified and controlled management regime on the experimental plots, as typically done under on-station conditions, the on-farm researcher is challenged to describe, quantify, and understand the management of the farmer that may, at times, seem unpredictable. These constraints have important implications for the selection of appropriate sites, plants, and parameters.

Site selection

In order to meet the objectives of the study on the one hand, and yet satisfy experimental requirements of homogeneity of treatment plots within blocks on the other, site selection was constrained by a series of conditions (Table 2-1). After intensive screening of coffee farms around Turrialba, 20 sites (see Table 2-2) were chosen that met these conditions. All sites were located on large farms because the requirements of homogeneity of soil conditions and of coffee and tree populations could not be met in small-farm operations with typically patchy management and heterogeneous plant populations. Furthermore, the large coffee farms had better management records and a higher chance of maintaining the experimental plots for a longer term. The next step was to select the plants to be included in each experimental plot.

Table 2-1. Conditions for selecting experimental sites on commercial farms to minimize nutrient or water competition between coffee and trees relative to shade effects.

The sites needed to have:

1. Similar soils to avoid or minimize soil X shade interactions since it was the goal to compare shade effects and not soil effects.

2. Soils of high nutrient status from natural high fertility and/or fertilization to assure that tree-coffee competition for nutrients would be minimized relative to the importance of shade.

3. Abundant rainfall throughout the year to minimize tree-coffee competition for water and hence shade X moisture interactions.

4. Homogeneous topography and soil sections within farms big enough to accommodate the different treatment and border areas. This condition was difficult to satisfy in undulating terrain such as that of the coffee zone around Turrialba.

5. A population of coffee plants within farms that is as homogeneous as possible in age, size, vigor, and production to reduce the number of plants needed for each plot.

6. An overstory of shade trees within farms that are as evenly distributed as possible in order to cast homogeneous shade on all coffee plants (homogeneous pre-experimental conditions).

7. Homogeneous management over the area that will accommodate the different treatments.

8. A continuous record of management activities since the plantation was established.

9. Collaborative and dependable farmers.

10. Easy access at all times of the year.

Plant selection

Since the treatments were to be installed in already productive coffee plantations rather than starting them from planting homogeneous seedlings on specifically chosen sites, the choice of sample size and the selection of the plants for the treatment plots had to consider that commercial plantations are typically more heterogeneous in terms of plant age distribution than experimental plots. This plant heterogeneity is due to substitution of individual plants that had declined in vigor and no longer responded to pruning. Over time, and hence more pronounced in already productive plantations, such selective substitution leads to a mixed age structure, and therefore a mix of vigor. The often larger soil heterogeneity on farms compared to on-station conditions may contribute substantially to this.

While working with such heterogeneity is generally deemed undesirable for experimental plots, it nevertheless represents the coffee producers' reality better than many homogeneous research station plots with nicely aligned, even-aged, and even-sized plants with individual-plant attention from which on-farm implications cannot be made. Working with more heterogeneous plant populations required two approaches for the design of this study: first, the

sample size for each treatment had to be increased above that of typical on-station experiments and, second, the populations had to be stratified in the field in order to exclude plants of extremely divergent stature or age.

Since data on the variability of production per plant under the on-farm conditions were not available, and plant size is related to production for similar-aged vigorous plants, the variability in plant size in the experimental plots was estimated and used to calculate sample size. According to Sokal and Rohlf (1981, p.263), sample size needed to detect a given difference between means can be calculated with the formula:

$$n \geq 2(CV/\delta)^2 * (t_{\alpha,\nu} + t_{2(1-P),\nu})^2$$

where n = minimum number of replications, CV = coefficient of variation, δ = the smallest difference to be detected, ν = degrees of freedom for the error, α = significance level, P = probability that a difference will be detected as significant and $t_{\alpha,\nu}$ and $t_{2(1-P),\nu}$ = values from a two-tailed *t*-table.

Exploratory size measurements of coffee plants gave a coefficient of variation (CV) of 0.04 to 0.08 for plant height and 0.04 to 0.16 for plant crown diameter. Taking an intermediate CV of 0.1, setting δ = 0.1 and expecting to be 80% certain to detect a difference among the four treatments at α = 0.05 gave a minimum number of 17 plants

per plot, assuming statistical independence among plants as replicates to avoid spurious results due to pseudoreplication (Hurlbert 1984). This sample size is larger than that of many field studies with coffee (Chavez et al. 1992; Ramirez 1993, pers. comm.). Given that the variability of size used for the calculations might underestimate the true variability of production, and anticipating the loss of some plants to unforeseen causes, I decided on a sample size of 25 plants per plot, which was a compromise between accuracy of the generated results and manageability of the experiments.

Parameter selection

The parameters to be evaluated were defined in consultation with the farmers involved. The final list of parameters and the detail of measurements were a compromise between scientific rigor and applicability with ease of measurement under field conditions. Considering the objectives of applied on-farm studies such as the one presented here, such compromises are acceptable and, in many cases, even necessary to shift efforts from data collection to interpretation and application (Hildebrand and Russell 1996). Details on the parameters assessed are given in Chapters 3-5.

Physical Setting of the Research Plots

Geography and Climate

The study sites with *Erythrina poeppigiana* (Chapters 3 and 4), *Citrus aurantium*, *Croton killipianus*, and *Eucalyptus deglupta* (Chapter 5) were located in coffee plantations of "Cafetalera Lindo S.A." (9°55'N, 83°41'W, 650-900 m a.s.l.), "Cafetalera Aquiares S.A." (9°57'N, 83°44'W, 700-1400 m a.s.l.), "Juan Viñas S.A." (9°55'N, 83°41'W, 700-900 m a.s.l.) and in Cervantes (9°55'N, 83°47'W, 950 m a.s.l.). All of these sites were on the Caribbean slope of Costa Rica within 3 to 20 km from Turrialba (Figure 2-1). Hence, these sites will collectively be referred to as the "Turrialba sites." The soils of the Turrialba sites were classified as Typic Hapludands (Soil Survey Staff 1992).

The data on coffee under *Casuarina equisetifolia* and *Cassia grandis* (Chapter 5) were collected in a plantation of "Quintas Montealegre" in the Central Valley of Costa Rica, referred to as the "San José site" (9°59'N, 84°13'W, 1000 m a.s.l.; Typic Haplustand). This location, one of the few remnants with *Cassia grandis* over coffee, was about 3 km WNW of the "Instituto Nacional de Aprendizaje (INA)" on the southern side of the highway leading to the Juan

Santamaría airport. Most sites were on flat or slightly inclined terrain with a slope of less than 5 % unless noted otherwise. The general characteristics of the permanent sites near Turrialba are summarized in Table 2-2.

On the bioclimatic map of Herrera and Gómez (1993), the environment of all plots is classified as humid subtropical to tropical. Due to their closeness to each other, all of the Turrialba plots were exposed to the same typical premontane climate of the Caribbean slope of Costa Rica. According to long-term temperature and rainfall data at CATIE, the climate of the Turrialba plots, adjusted for elevation[1], is characterized by mean annual temperatures of 18-22°C with only small monthly variations (Figure 2-2), an average annual precipitation of 2600 mm and annual evaporation of 650 mm (Piché) or 1150 mm (Tank A) (Jiménez 1997)(Figure 2-2). This information can be used as reference for the majority of the plots.

The main climatic difference between the Turrialba and San Jose plots is the marked 4-6 month dry season centered on February in San José which is much less marked in Turrialba. In Turrialba, only the months January through

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[1] The elevational decrease of temperature was assumed as 0.6° per 100 m of altitude. Rainfall was not measured in the plots. Given the high rainfall throughout the year, the effects of possible small differences among plots at different elevations were assumed negligible.

Table 2-2. Description of the research sites near Turrialba.

Name and code of site	Farm and location	Elevation (m a.s.l.)	Treat-ments (*)	Observations
El Cañal (E1-E4) (&)	Lindo, Turrialba	700	T1-T4 (+T5 in E1)	E1 and E2 with Caturra; E3 and E4 with Catimor 5175
El Mendez (E5-E6)	idem	700	T1-T4	E5 NE exposure E6 flat
El Galicia (E7)	idem	800	T1-T4	SE exposure, 30% slope
El Vargas (E8-E9)	La Isabel, Juan Viñas	800	T1-T4	coffee pruned by rows
El Alto de la Isabel (E10)	idem	1000	T1-T5	SW exposure, 20% slope
El Bananal (E11)	Lindo, Turrialba	900	T1-T4	in depression, drainage problems
Palo Mechudo (E12-E15)	idem	950	T1-T4	NW exposure, up to 30% slope
El Capinal (E16)	Lindo, Esmeralda	1000	T1-T4	SE exposure, < 10% slope
Aquiares abajo (E17-E18)	Aquiares	850	T1 vs T5	sun vs. Shadecloth comparison
El Onze (E19)	idem	1100	T1 vs T5	rocky soil, plants of low vigor
El mirador (E20)	idem	1400	T1 vs T5	S exposure, 20% slope

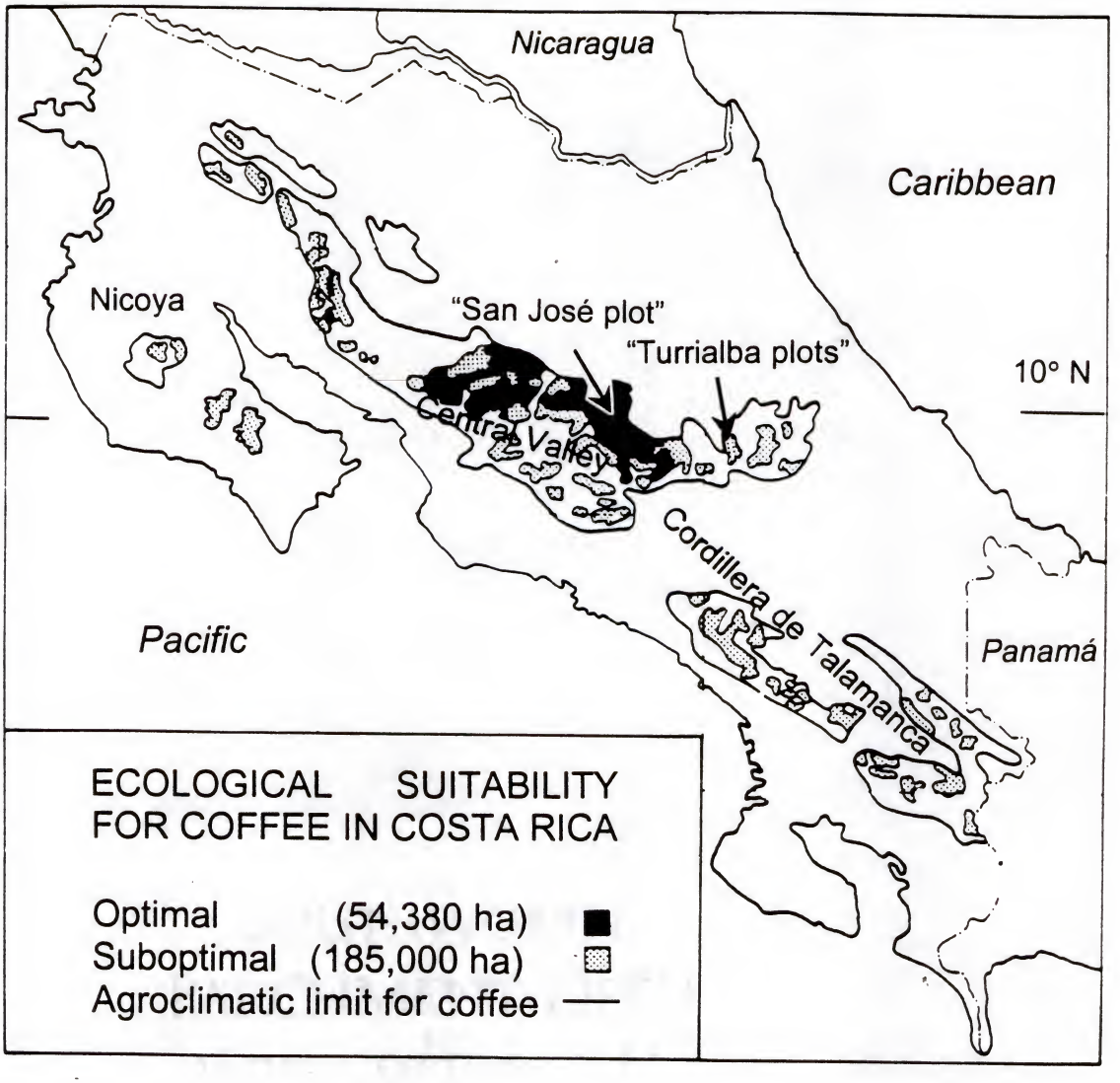

Figure 2-1. Optimum (black) and suboptimum (shaded) regions for *Coffea arabica* L. in Costa Rica, and location of the experimental plots in Turrialba and San José (map modified from SEPSA in ICAFE-MAG 1989).

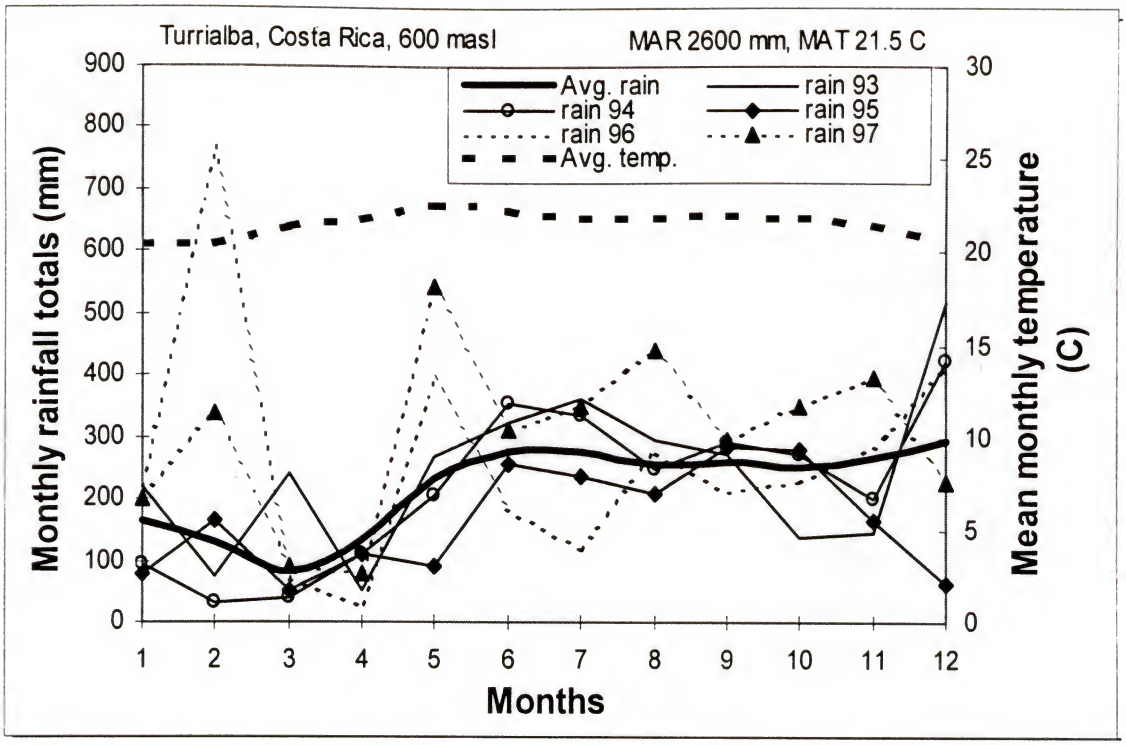

Figure 2-2. Monthly rainfall totals for the years 1993 through 1997, long-term means of monthly rainfall (44 years), and mean monthly temperatures (25 years) for Turrialba, Costa Rica (data from Jiménez 1997).

April show on average precipitation below the monthly mean of 218 mm. The unpredictability of the "dry season" in Turrialba is illustrated by the extremely high rainfalls that occurred during February and May of 1996 and 1997 (Figure 2-2). The mean number of sunshine hours per month varies little from 116 in July to 163 in March. This corresponds to 37 - 53 % of the theoretical maximum. Relative humidity fluctuates very little from 85% in March to 90% in November.

In Turrialba, both the mean annual temperature and the annual rainfall exceed the "ideal" values given by Carvajal (1984) (cf. Chapter 1), by 1.5° C and 900 mm, respectively. This, together with a weak or absent dry season makes Turrialba's climate suboptimal to marginal for coffee (Rojas 1989).

Geology and Soils

The main geological units in Costa Rica date from Jurassic to Quaternary times and form a patchwork of sedimentary rocks, plutonic intrusions, and volcanic rocks (Castillo 1993). The soils on the Turrialba sites of this study developed primarily from quaternary volcanic rocks originating from the Turrialba volcano whose main craters are at about 15 km from Turrialba at 3328 m a.s.l. The sites studied formed a toposequence from 650 m a.s.l. to 1400 m a.s.l. on soils derived from the geological formation "Colada de Lava de Aquiares" (Dondoli and Torres 1954). Paniagua (1984) classified the parent material of the soils as andesitic and andesitic-basaltic with relatively high contents of K (1.9 % K_2O) and 55% of SiO_2. The parent material of the San José site consists also of andesitic rocks mixed with pyroclastic and ash deposits derived from the geologic formation "Andesitas Poás" (Castillo 1993).

Soil profiles on selected sites were described in detail during the study (for methodology refer to Chapter 3). The chemical characteristics of the soil at "El Cañal" are given in Table 2-3. This soil can probably represent also the other soils of the Turrialba sites, considering that they are all derived from the same parent material, with similar climate, exposure, and land-use history. Similarity of soil conditions was an important criterion for site selection. Therefore, care was taken that the visual evaluations of profiles at all sites did not reveal large deviations from the description given in Table 2-3. The largest difference among the soils chosen was due to stone content which ranged from 0 to about 20% by volume. Although the San José soil was not analyzed chemically, its visual appearance, structure and texture along a 50 cm deep profile, as well as its similar geologic origin make it similar to the Turrialba soils.

I classified the Turrialba soils as acid isothermic (to isohyperthermic) coarse-silty Typic Hapludands (Soil Survey Staff 1992). The longer dry season at the San José sites made those soils Typic Haplustands. On all sites, the soils were homogeneous and had favorable physical properties. Good structure and high infiltration capacities were typical of Andisols. Except for single boulders,

Table 2-3. Soil profile description for the experimental plots of "El Cañal", Finca Cafetalera Lindo S.A., Turrialba, Costa Rica (650 m a.s.l.; 2300 mm; 22°C).

CLASSIFICATION:	Typic Hapludand
LOCATION:	El Cañal, 1 km SE of Sta Rosa de Turrialba, Costa Rica
ELEVATION:	650 m a.s.l.
PHYSIOGRAPHY:	rolling footslopes of Turrialba volcano
SLOPE:	flat
PARENT MAT.:	andesitic rocks, pyroclastics, ashes
LAND USE:	Coffee plantation with *Erythrina poeppigiana* for > 20 years
LIFE ZONE:	humid, premontane, no dry season
CLIMATE:	MAR 2300 mm, MAT 22°C
SOIL CLIMATE:	isothermic/isohyperthermic, udic
DATE DESCRIBED:	11-93 (visual, tactile, soil pit and coring); 11-97 (soil pit, chemical analyses)

Horizon	Description
A	0-10 cm; very dark brown (10 YR 2/2); silty loam, subangular and crumb structure; thixotropic; common roots; common fine pores; gradual boundary.
A/B	10-40 cm; dark brown (10YR 3/2); silty loam with small friable parent rocks; subangular and crumb structure; thixotropic; common roots; common fine pores; on 5% of profile wall yellowish brown (10 YR 5/6) concretions of < 2 cm diameter; gradual boundary.
B	40-60 cm; dark brown (10 YR 4/3) to dark yellowish brown (10 YR 4/4); silty loam with medium-sized sand particles (Gesteinsgrus) and soft weathered crumbling parent material of < 10 cm diam on 5-10% of profile wall; gradual transition.
B/C	60+ cm; yellowish brown (10 YR 5/4 to 5/6); colors brighten up; transition to friable saprolite which is cut through on 30-50% of profile wall.

Table 2-3 continued. Values represent unreplicated composite (n = 5) samples.

Horizon	Depth (cm)	O.M. (%)	pH (H_2O)	N tot (%)	P[$] mg kg^{-1}	K[$] cmol kg^{-1}	Al+H[&] cmol kg^{-1}
A_{sun}	0-10	6.4	5.0	0.42	9.15	0.28	1.94
A_{shade}	0-10	8.9	5.5	0.49	9.15	0.28	0.22
A/B	10-40	3.4	5.7	0.24	3.52	0.08	0.22
B	40-60	1.7	5.8	0.12	1.55	0.04	0.22
B/C	60+	1.4	6.0	0.11	1.83	0.05	0.14

Horizon	Depth (cm)	Ca[&] cmol kg^{-1}	Mg[&] cmol kg^{-1}	Cu[$] mg kg^{-1}	Zn[$] mg kg^{-1}	Mn[$] mg kg^{-1}
A_{sun}	0-10	8.1	2.3	23.5	3.4	43.0
A_{shade}	0-10	10.8	3.1	10.0	2.5	45.0
A/B	10-40	14.8	4.4	5.1	0.6	6.8
B	40-60	14.6	5.7	3.2	0.3	2.7
B/C	60+	12.3	4.0	5.6	0.3	3.5

Horizon	Depth (cm)	CEC[#] cmol kg^{-1}	Ca[#] cmol kg^{-1}	Mg[#] Cmol kg^{-1}	K[#] cmol kg^{-1}	Na[#] cmol kg^{-1}	BS %
A_{sun}	0-10	40.0	9.7	2.7	0.68	0.04	32.7
A_{shade}	0-10	37.4	12.7	3.7	0.66	0.05	45.6
A/B	10-40	40.3	17.7	5.5	0.23	0.07	58.2
B	40-60	38.4	17.5	7.2	0.10	0.07	64.6
B/C	60+	33.7	14.9	4.8	0.09	0.08	59.0

[$] extraction with modified Olsen solution
[&] extraction with 1N KCl
[#] extraction with 1N ammonium acetate at pH 7.0

probably remnants of past mudflows, and up to 20% (by volume) of large stones on some sites, no physical barriers to rooting were detected. The values given in Table 2-3 were derived from single composite samples (cf. Chapter 3) to characterize the soil chemistry. Since the regular nutrient inputs in the form of fertilizers (cf. Chapter 3) were likely to dominate the nutrient budgets, no attempt was made to replicate the sampling to permit statistical analysis of nutrient concentrations.

The pH-values in the topsoils ranged from 4.6 to 5.5 in H_2O and were therefore in the range of moderately to very strongly acid (Agric. Compendium 1989). The pH-values increased slightly with depth (Table 2-3), probably reflecting leaching of bases from the topsoil and surface acidification through fertilization, especially ammonium nitrate (cf. fertilization practices described in Chapter 3). The concentrations of organic matter (OM) ranged from very high (up to 8.9%) in topsoils to low (< 1.8%) in subsoils below 40 cm depth (Table 2-3; Agric. Compendium 1989; Díaz-Romeu 1982). The topsoil contents of 3.7% to 5.2% organic carbon (OC; conversion: OM = 1.72 * OC; Díaz-Romeu 1982) exceeded the mean OC content of 2.96% in 167 Ah-horizons of Central America (Díaz-Romeu et al. 1970), of which 57 % showed OC contents between 1% and 2.5%. Total

nitrogen contents were high (> 0.4%) in the topsoils, probably as a result of fertilization, and medium to low in the subsoils (Agric. Compendium 1989). Using the categories given by Bertsch (1995), the levels of aluminum ranged from low levels of < 0.5 cmol kg^{-1} of extractable acidity in the subsoil of "El Cañal" (Table 2-3) to high levels exceeding 2 cmol kg^{-1} in the topsoil of some sites. The nutrients in shortest supply, especially in the subsoil, were P and K (Table 2-3).

The levels of P in all horizons were below the critical level of 10 mg kg^{-1} given by Bertsch (1995) and K showed medium levels in the topsoil and extremely low values (< 0.2 cmol kg^{-1}) in the subsoil. However, it is likely that these values of P and K underestimate the average nutrient availability over the course of the year given that the sampling was done about six months after the last fertilization and just prior to the next one. Also Ca, Mg and the micronutrients Zn, and in some cases, Mn were below their optimum levels (Table 2-3). The low levels of P were probably due to the high P-fixation of soils rich in active aluminum such as allophane-rich volcanic soils (van Wambeke 1992). The low levels of Ca and Mg result possibly from the low nutrient retention capacity of Udands (van Wambeke 1992) and the high acidity and rainfall which

increase leaching losses. Despite the high infiltration capacities of the soils there was local evidence of sheet erosion and growing erosion channels resulting from surface runoff during high-intensity rainfall events. However, even on the most inclined sites in Aquiares, no measures for physical soil retention had been taken. Nutrient deficiencies of the soils were ameliorated with chemical fertilizers. Details on fertilization are given in the section on plant and soil management in Chapter 3.

Vegetation and Land-Use History

The experimental sites were located in the life zone of tropical premontane wet forest (Holdridge 1967). Since the early 19th century, the original mixed broad-leaf forests have been increasingly replaced by agricultural systems dominated by coffee (*Coffea arabica* L.), sugarcane (*Saccharum officinale*), bananas (*Musa* spp.) and a broad range of annual or biennial agricultural crops. The sites of this study located on the properties of "Cafetalera Lindo S.A.", "Cafetalera Aquiares" and "Juan Viñas" have been under coffee with the associated legume tree species *Erythrina poeppigiana* for more than 20 years, some for more than 50 years. While it was the tradition to cultivate coffee under a more or less dense shade of *Erythrina* and other tree species such as *Inga* spp., *Citrus* spp., and *Musa*

spp., the past two decades witnessed a strong intensification of coffee management. This intensification consisted of increasing use of agrochemical inputs and partial or complete elimination of trees associated with coffee to minimize potential negative effects of the trees on coffee. Since these changes require financial inputs, they have been more pronounced on largescale operations where cash and credit are more readily available than on smallscale family farms. The reduction of the trees' effects on coffee was achieved by more intense pruning or pollarding or by their complete removal. Eliminating trees resulted in a marked reduction of tree species diversity in coffee from originally over 50 species (Espinoza 1985) to often one or none, a development with potentially large ecological effects reaching beyond the local impact of individual trees. The loss of trees in coffee fields is, among many effects, often the cause for a marked reduction of soil fertility, water retention, and the diversity of different groups of organisms with a broad spectrum of ecological functions (Rice 1991; Wille 1994; Perfecto et al. 1996; Greenberg et al. 1997).

A substantial area of the coffee lands, especially of Aquiares, forms part of the catchment areas for drinking water of Turrialba and adjacent communities. The quality of

this water is also likely to be affected by the recent changes in land-use intensity and pesticide use (Castillo et al. 1997). Consequently, if shaded and diverse coffee fields are more valuable for biodiversity and clean water generation than sun-exposed high-input monocultures (Perfecto et al. 1996), the importance of trees in coffee fields extends even beyond their effects on coffee which will be treated in the following chapters.

CHAPTER 3
COFFEE PRODUCTION UNDER *ERYTHRINA POEPPIGIANA*

Introduction

The question whether coffee plants benefit or suffer from an association with trees is as old as coffee production itself. Early accounts (e.g., Lock 1888; Cook 1901; Alvarado 1935; Rodriguez 1935) as well as more recent reviews (Willey 1975; Maestri and Barros 1977; Fournier 1988; Barros and Maestri 1995; Beer et al. 1998) summarize contradictory evidence about the values of shade for different coffee areas.

An early shade advocate from Guatemala described the importance of shade with the words (translated from Spanish) "It is astonishing that what cannot be achieved with other costly options can be solved by a few trees for protection" (Alvarado 1935, p.47). However, not much later, other workers started to propose sun-grown coffee as the more productive alternative (e.g., Suarez de Castro and Uribe 1957; Cowgill 1958).

Today, the apparent contradictions of research results, and derived contradictory recommendations, illustrate that

the debate is still alive (Muschler 1997b; Beer et al. 1998). For example, while shade and nutrients from pollarded *Erythrina poeppigiana* were found to be highly beneficial for unfertilized *Coffea arabica* in a 10-year study in Turrialba at 650 m a.s.l. (Ramirez 1993), their benefits for unfertilized coffee were much smaller, yet still marked, at 1375 m a.s.l. (Ramirez 1997). Given similar soils and management inputs, it is likely that other differences in the biophysical environment, particularly elevation, may have played the key role in determining the treatment responses.

Overall, it seems that beneficial effects of trees are, and were in the past, predominantly linked to suboptimal areas for coffee (cf. Chapter 1). Despite the dearth of gradient studies designed to compare coffee responses in optimum versus suboptimum environments (Casper and Jackson 1997), most of the work in plant ecology seems to support the conjecture that shade benefits from trees towards other plants tend to increase with environmental harshness (Callaway and Walker 1997). To examine this, the following study was set in a suboptimal coffee region of Costa Rica.

Around Turrialba, a low-elevation coffee zone of Costa Rica with suboptimal biophysical conditions for coffee (ICAFE-MAG 1989; Rojas 1989; Herrera and Gomez 1993) due to

high temperatures and moisture (cf. Chapter 2), most coffee plantations are associated with *Erythrina poeppigiana* to provide shade, organic matter and nutrients via leaf fall, pruning residues, and root turnover (Beer et al. 1998). Typically, the shade trees are pruned two or three times per year to stimulate coffee flowering between January and March, and to speed up maturation of coffee berries from August onwards. In many cases the trees are pollarded, i.e., all branches are removed at the same time causing abrupt microclimatic changes (see sections on shade patterns and microclimate on pp. 67 to 72). In other cases, some branches are left untouched to provide intermediate and less fluctuating shade, typically permitting a transmission through the tree crowns of 30% to 70% of the photosynthetically active radiation (PAR) available in the open sun. On still other farms, the trees are not pruned at all, and the projected shade is subject only to the phenological cycle of the trees. In the latter case, shading can exceed 70%, i.e., reduce the available PAR to less than 30% of the PAR under the unobstructed sun.

While the debate about the ideal level of shade for *Coffea arabica* L. continues (e.g., Fournier 1988; Muschler 1997b; Beer et al. 1998; Fernandez and Muschler 1998), and many primary research articles present data of different

detail on responses of coffee to shade (e.g., Nunes et al. 1993; Ramirez 1993; Fahl et al. 1994; Ramirez 1997; Muschler 1997a), there is, unfortunately, very little quantitative information to support either of the claims (Beer et al. 1998; Muschler 1997b). Many, if not most, of the articles published on shade lack adequate quantification of the shade levels used (e.g., Montealegre 1954; Suarez de Castro et al. 1961; Ramirez 1993; Aldazábal and Alarcón 1994a; Guyot et al. 1996; Ramirez 1997) which hinders interpretation and application of the data.

Other publications report data from individual plants, or even plant parts, often evaluated under laboratory conditions for only short periods during juvenile growth (e.g., Tanada 1946; Huerta 1954; Nunes *et al.* 1968; Nunes *et al.* 1993; Fahl *et al.* 1994.) which limits the extrapolatibility of the information to the plantation level. Consequently, the relevance and transferability of information from such publications to commercial plantations is often strongly compromised. Unfortunately, working at the plantation scale typically requires more time and money which is why results at this scale are relatively rare (Maestri and Barros 1977; Wrigley 1988).

To reduce these information deficits, a field experiment was set up on commercial coffee plantations around Turrialba. The specific objectives were to:

1. Quantify the effects of different shade levels on environmental parameters for coffee (microclimate, soil, and weeds).

2. Determine the effect of different shade levels under *Erythrina poeppigiana* on production, vigor, and diseases of coffee under on-farm conditions.

Materials and Methods

The experiments with different levels of tree shade were established between September and December of 1993 in coffee plantations of the Atlantic coffee region around Turrialba, Costa Rica.

Research Sites

The plots were located in coffee plantations of "Cafetalera Lindo S.A.", Turrialba (9°55'N, 83°41'W, 700-900 m.a.s.l.; mean annual temperature MAT 19-21°C; mean annual rainfall MAR 2600 mm; no marked dry season) and the section "La Isabel" of "Juan Viñas S.A." (9°55'N, 83°41'W, 700-950 m.a.s.l.; similar climate), all within 20 km from Turrialba, Costa Rica (Table 2-2, Fig. 2-1, Chapter 2). The sites were chosen to have similar and homogeneous soils and relief, and to cover a range of elevations and aspects (Table 2-2). The soils were classified as Typic Hapludands with a pH_{H2O} of the

topsoils ranging from 4.6 to 5.5 and intermediate levels of nutrients, except for low levels of P and K, at least at the time of sampling which was six months after the last fertilization (for details see Chapter 2). Further prerequisites for site selection were, as far as possible under on-farm conditions, homogeneous plant populations of *Coffea arabica* L. and *Erythrina poeppigiana* (Walpers) O.F. Cook (cf. Chapter 2). Homogeneity of ages and sizes of coffee plants helped to maintain the sample sizes relatively small (Chapter 2), and homogeneity of the *Eythrina* stratum resulted in a uniform shade pattern affecting each coffee plant similarly as had been the case for two years prior to establishing the experimental plots.

Coffee and Tree Management

The plants of the systems studied were two of the most important commercial varieties of *Coffea arabica* L., Caturra and Catimor (Wrigley 1988), the latter represented by the selection Catimor 5175, and the N-fixing leguminous tree *Erythrina poeppigiana* (Walpers) O.F. Cook. This species of *Erythrina,* commonly referred to as "poró," is a widely-used shade tree in Costa Rica (Beer et al. 1998). At the establishment of the experiments, the coffee plants were between six and ten years old, and the shade trees of *Erythrina* between 10 and 15 years. The typical planting

density of coffee was 2 m by 1 m corresponding to approximately 5000 plants per hectare. With few exceptions, distances between *Erythrina* trees ranged from 8 m to 10 m. Coffee management was intensive (for details see Appendix) with two fertilizations of 315 kg ha^{-1} yr^{-1} of complete fertilizer (18-5-15-6-2; N-P-K-Mg-B), 315 kg ha^{-1} yr^{-1} of ammonium nitrate (33.5% N) and 250 kg ha^{-1} yr^{-1} of $CaCO_3$. Furthermore, micronutrient solutions, containing B and Zn (each at 0.75 kg ha^{-1} yr^{-1}) were applied as foliar sprays to the coffee three times per year. The coffee was subject to selective pruning at the beginning of each year to remove senesced stems and branches that did not have enough juvenile growth or vigor to carry fruits in the future. This pruning system is the most widely used in Costa Rica (Alvarado and Rojas 1992). Weeds and diseases were controlled with herbicides (Paraquat® and Gardoprim® at 5 L ha^{-1} yr^{-1} each; Goal® and Roundup® at 2.5 L ha^{-1} yr^{-1} each) and fungicides (Atemi® and Cu, each at 0.75 L ha^{-1} yr^{-1}) split-applied at, on average, three or four times per year. Nematicides were applied once per year at 22.5 kg ha^{-1} of Counter®. All plots were managed identically except for not applying herbicides in the "open" and "dense" shade plots where permanent shade suppressed weed growth (cf. treatment

descriptions and microclimatic characterizations in Table 3-1 and in the sections on shade patterns and microclimate).

Treatments and Experimental Design

Between October and December of 1993, five shade treatments (T1 to T5; Table 3-1; Figure 3-1) were imposed on homogeneous coffee plots at 16 sites (Table 2-2). The treatments were the result of the need to have (i) shading extremes (sun and dense shade) and intermediates (pollard, open shade, shadecloth), and (ii) to represent traditional management practices (sun, pollard, and dense shade). They covered a range of shading from 0% in the sun treatment to a yearly average of 86% in the dense shade treatment (Table 3-1; Figure 3-3). The shadecloth (50% shade according to the manufacturer) projected an intermediate shade that was homogeneous in space and time.

Each one of the treatments sun, pollarding, open shade, and dense shade was represented as one plot per site, and each site was considered as one block of a randomized complete block design. For cost reasons, the shadecloth treatment (T5) was established at only two of these sites. Of the experiments originally established at 16 sites (E1 to E16 in Table 2-2), E8 and E16 were damaged by careless coffee pruning during the first year. On the 14 sites left,

Table 3-1. The shade treatments and their management (El Cañal, Turrialba, Costa Rica; 700 m a.s.l., 2600 mm rainfall per year)

Abbrev.	*Treatment*	*Management*
T1	Sun	Continuous pollarding of *Erythrina* stems at 1.8 m to 2 m above the ground (trees without branches).
T2	Pollarding[&]	Pollarding of *Erythrina* stems at 1.8 m to 2 m above the ground 3 times per year; 3% to 50% shade; maximum crown diameter prior to pollarding ranges from 1.5 m to 3 m; maximum tree height from 3 m to 4 m.
T3	Open shade[&]	Pruning of selected branches; 46% to 78% shade; crown closure is achieved; tree height ranged from 6 m to 12 m.
T4	Dense shade[&]	Dense canopy of *Erythrina*; no pruning: 77% to 90% shade during the first two years (measured); thereafter 60% to 80% (estimated)
T5	Shadecloth[&]	Artificial shading (black shadecloth) labeled 50% shade) measured as 55% to 60% shade

[&] for characterization of shade pattern over the year and of microclimatic parameters refer to the sections "Shade pattern" and "Microclimate" starting on page 67.

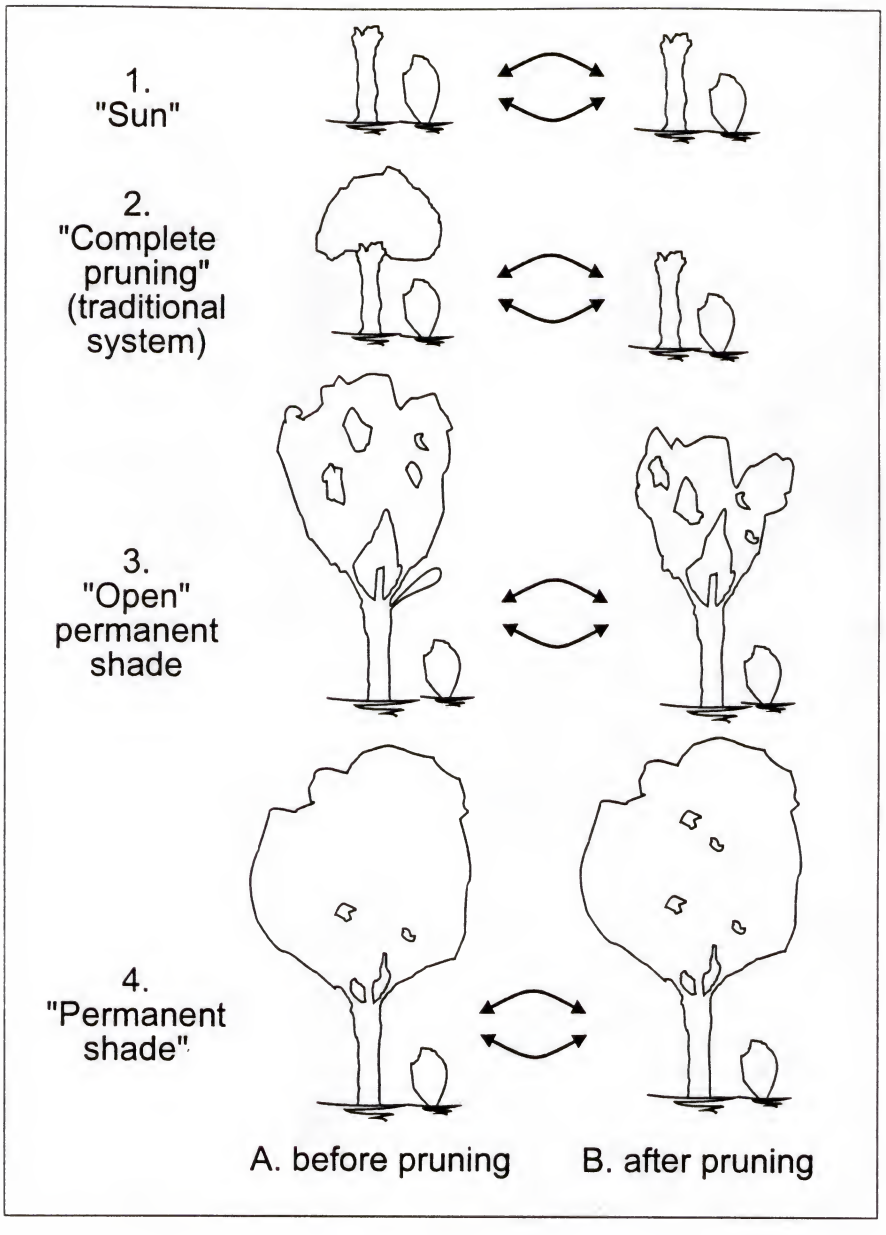

Figure 3-1. Shade treatments with *Erythrina poeppigiana* resulting from different pruning intensities. Shade intensity increases from treatment 1 (0% shade) to 4 (77% to 90% shade). The arrows represent the changes between the stages A and B due to pruning and resprouting of the trees. The small plants represent coffee bushes.

the potential production (see methodology below) was estimated for two years after treatment establishment (i.e., the harvests 1994/95 and 1995/96). In addition, on four of these sites, located close to each other and referred to as the "Central Experiment" in "El Cañal," coffee was harvested biweekly during four years to assess actual harvest, harvest losses, and bean quality. Since the relative effects of shade on the 1995/96 estimates[1] of potential production and vigor were unexpectedly similar among the 14 sites, and logistical limitations did not permit to collect actual harvest data from plots other than those of the Central Experiment, I decided to maintain only the plots of the Central Experiment. Here, the four treatments with *Erythrina* were repeated in four blocks (two for Caturra and two for Catimor 5175) which were analyzed as a RCBD. The shadecloth treatment, represented only by one plot with Caturra, was not included in the statistical analysis. The plots of the Central Experiment were used for detailed microclimatic studies and long-term evaluation of harvest and vegetative attributes of the coffee plants. For those reasons,

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[1] The first year's potential production data (harvest 1994/95) have to be interpreted with caution since they were, to unknown extent, affected by pre-experimental shade rather than solely by the shade treatments.

primarily the data from the Central Experiment in "El Cañal" are reported in the following.

At the time of treatment establishment, the coffee plants had been exposed to increasing levels of shade from a closed canopy of *Erythrina poeppigiana* that had not been pruned for two years. The two-year suspension of pruning was an attempt to suppress flowering during this time and to trigger synchronized flowering by sudden removal of the shade after two years. Lack of synchrony in flowering and fruit development, a problem in areas without a strong dry season such as Turrialba, tends to stretch the harvest period (and hence the harvest costs) by several months (Wrigley 1988). The treatments were imposed by selective shade removal according to the treatment descriptions (Table 3-1).

Plots and Sampling

Including the border areas, the sides of each plot measured between 25 m and 40 m. In some cases, missing coffee plants or *Erythrina* trees made it necessary to increase plot size. The net plots consisted of 25 individually labelled plants each (for the derivation of sample size see Chapter 2) which occupied, typically, an area whose sides were between 10 m and 15 m long. The shadecloth plot measured 8 m by 18 m. The net plots were

separated by border strips of 10 m to 30 m width. This distance was large enough to avoid substantial shading interference of the tall-tree treatments (open and dense shade) on neighboring plots, and it was small enough to avoid problems of site heterogeneity which is likely to become a problem when plots are separated further. The total experimental area in the Central Experiment comprised approximately one hectare. Although superficial roots of *Erythrina* were, on some sites, found to extend beyond 15 m from the tree stem (data not presented), root interactions were assumed to be negligible due to the high fertilization and moisture availability of the site (cf. Chapter 2, and the section on coffee and tree management in this chapter).

Parameters and Statistics

This section presents the environmental parameters measured, the coffee parameters evaluated and the statistical tools used to analyze the information.

Environmental parameters

PAR-transmission. Shading was measured monthly as interception of photosynthetically active radiation (PAR) relative to open sun, using a Sunfleck Ceptometer (Decagon Devices Inc.) with 40 quantum-sensors along a 40 cm long probe. The individual sensors are automatically scanned during every measurement which allows a large number of

spots to be sampled in a relatively short period of time. All measurements were taken above the crowns of the coffee, i.e., at 1.8 m to 2.2 m, on cloudless days within a two-hour period centered on solar noon.

The shade level of each plot was calculated as the average of 50 measurements (i.e., as the mean of 2000 spot measurements) that were taken at 1 m distances along a 50 m line transect, holding the probe perpendicular to the transect. The transect was folded in a zig-zag manner to traverse the net plot from border to border. Care was taken to use a similar (albeit not identical due to some plot irregularities) path for all plots originating in the NE corner and ending in the SW corner of each plot. For the calculation of radiation transmission, reference measurements of the unobstructed sun, taken before and after each transect, were averaged. The sequence of measurements for the treatments within each block was changed among blocks, so that each treatment was the first, second, third, or fourth to be measured in exactly one block; this corrected for changes of the sun's position during the period of measurement.

Relative humidity (RH) and air temperature. RH and air temperature were measured hourly on typical sunny and windstill days in El Cañal using a sling psychrometer

(PRINCO Instruments Inc.). The instrument was rotated at a constant speed of approx. 2 rotations per second, which aspirates the wet bulb at about 3 m s^{-1} , a value comparable to the standard Assmann psychrometer (Monteith and Unsworth 1990). After rotating the instrument for 90 seconds, the temperature difference between the dry and the wet thermometers was noted for later derivation of the RH and the corresponding vapor pressure deficit (VPD). The readings of the dry thermometer were also taken as temperature readings. The measurements were taken at 1.5 m above the ground at three randomly chosen locations within each plot. The sequence of plots measured was changed between repetitions.

Soil and leaf temperatures. Soil temperatures were measured at 2 cm depth of three randomly selected shaded and sun-exposed plots. The temperature sensor, an electronic thermometer with external sensor (Fielmann Corp., Germany). was left in the soil until the readings stabilized, typically after one minute. Leaf temperatures were taken with a copper-constantan micro-thermocouple held to the upper surface of three randomly selected shaded and sun-exposed leaves. During the measurements, all sensors and cables were shaded to avoid effects due to direct sun exposure.

Soil sampling. Soils pits were dug to 0.7 m depth at all sites to permit visual characterization, and description of soil texture, structure, and color. Soil sampling for chemical characterization of the soil in the Central Experiment was based on unreplicated composite samples (10 randomly located subsamples from the center between coffee rows). The laboratory procedures followed the methods described by Díaz-Romeu and Hunter (1982) and Díaz-Romeu (1982). Total N was determined with the micro-Kjeldahl method (Bremner and Mulvaney 1982).

Weed/litter cover and biomass. Weed cover was assessed as an ocular estimate of the proportion of the soil surface covered by living weeds. Weed biomass was measured by clipping the weeds in five randomly located 0.4 X 0.6 m plots in each treatment. In the tall tree shade plots (open and dense shade), litter biomass on the ground was measured in the same way. All samples were dried at 65°C to weight constancy.

Coffee and tree parameters

Foliar biomass and samples. After measuring the fresh weights of pruned *Erythrina* leaves and branches, conversion factors to dry weight were determined from drying samples of 1 kg of leaves or branches at 65°C to weight constancy. For

standard foliar analysis of coffee, following Huerta (1964), the fourth pair of leaves was taken (unless noted otherwise) from five randomly selected branches on each of ten randomly selected plants (i.e., 100 leaves per sample). Coffee plants were sampled in December 1995 and November 1997, i.e., during the last quarter of the harvest period when they were most stressed. Duplicate composite samples of *Erythrina* foliage were taken of pruned materials and of freshly-fallen senesced leaves.

Plant dimensions. Basal stem diameter of coffee was measured as the average of two perpendicular measurements at 10 cm above the soil surface or above the lowest knot in case of irregular trunks. Basal diameter of productive branches was measured at 10 cm above the point of insertion into the main stem. Plant height was defined as the vertical distance from the ground surface to the average height of the two tallest shoots. Crown diameter was assessed as the average of two horizontal measurements between the crown edges (in row direction and perpendicular to it). The crown edge in each direction was defined as the center of the straight line that connected the most distant points of the ground projections of the two branches with greatest horizontal extension in that direction.

Coffee production. The total production of a coffee bush can be disaggregated into the following components:

$$TF = QF + RF + FF \qquad \text{(Equation 3-1)}$$

where TF is the total number of fruits set per plant (= "potential production"; a product of the number of flowers formed and the flower-to-fruit conversion factor); QF is the proportion of quality fruit, RF is the proportion of rejected fruits (consisting of deformed, dried, sun-burnt, diseased and mummified berries), and FF is the quantity of fallen fruit.

For the Central Experiment, coffee production was measured from July 1994 to January 1998 by summing the fresh weights of coffee fruits harvested from the 25 plants per plot over the 10-12 biweekly harvest events of each season. Yield was calculated in two ways: first, as total fruit yield harvested (including rejects, i.e., QF + RF in Equation 3-1), and, second, as "quality fruit" yield without rejects (QF). Since these measurements are tedious and require much labor and coordination with the commercial pickers of the farm during the six to eight months of harvest per year to avoid that fruits are accidentally picked from experimental plants, I estimated also the total number of green fruits on each plant before the first

picking. This number equals the potential production (= TF) of the plant if all fruits were to develop to mature. While the actual harvest data are undoubtedly closer to the farmers' reality (and hence used as the reference for the data presented), the potential production data have the advantage of relying only on a single measurement. This makes the assessment faster and eliminates problems with loss of fruits picked by other workers or falling off the plant before harvest - both cases would result in underestimating the fruit production of the plant.

For estimation of potential production, the number of fruits on each pair of opposite productive branches was estimated in classes of 50 and added over all pairs of branches and stems of each coffee plant. To assure that all branches were included and to avoid double counting, the evaluation was always started at the top-most productive pair and then descended the decussate branch pairs of the rubiaceous plant. The number of fallen fruits at the end of the harvest period was assessed by counting berries on the ground in five 0.4 m by 0.4 m squares that were randomly located within the crown perimeter of coffee bushes.

Foliation and diseases. Foliation of the plants was assessed on a relative scale of 0 to 10 with 10 representing a plant with all of its leaves (two per node) and 0

representing a plant with no (living) leaf. The index of 5 applied to plants that retained 50% of their foliage. Foliar and fruit infection was estimated for the following diseases that are widespread problems in coffee in Costa Rica (ICAFE-MAG 1989): *Cercospora coffeicola* ("Chasparria"), *Hemileia vastatrix* ("Roya" = leaf rust), *Mycena citricolor* ("Ojo de gallo") and *Colletotrichum* spp. ("Antracnosis"). Infection level was quantified for each plant as an ocular estimate of the percentage of leaves or fruits with more than 5% of their surface infected. This estimate was found to correspond well with the infected-leaf-count method described by Von Chong and Bonilla (1990) and by Monterroso and Calderón (1995), while being non-destructive and faster. To correct for time-induced biases of the ocular estimates, all treatments at each site were evaluated in one session, and the evaluation sequence of plots was alternated from site to site.

Statistical analyses

Means were compared with ANOVA and t-tests. Where the basic assumptions for ANOVA were violated, data were transformed, or subjected to non-parametric tests. Multiple mean comparisons followed Duncan's Multiple Range Test and orthogonal contrasts for group comparisons. Differences were declared significant for $\alpha \leq 0.05$.

Results

Since the "satellite experiments" E5 to E15 (Table 2-2), which were monitored less intensively and only for two years, yielded similar production and disease results as the Central Experiment (E1-E4), I focus primarily on the results of "El Cañal". Harvests were assessed from 1994/95 through 1997/98. However, since the productions of 1996/97 and 1997/98 were affected not only by unusual rainfall events during flowering (chapter 2: Fig. 2-2), but also by the phenology of the then-mature tree crowns (of decreasing crown density with age) in the open and dense shade treatments, I present certain data (e.g., cumulative harvest in Figure 3-8) only for the harvests 1994/95 and 1995/96 which correspond closely to the shading patterns described in Figure 3-3, and the rainfall patterns of typical years. The main effects of the shading treatments will be presented in two sections: (i) environmental modification and (ii) coffee responses. The order or the subsections follows the numbering in Figure 3-2. Effects of shade on coffee quality will be presented in Chapter 4.

Environmental Modification

This section is divided into four parts: shading patterns, microclimate, soil parameters, and weed growth.

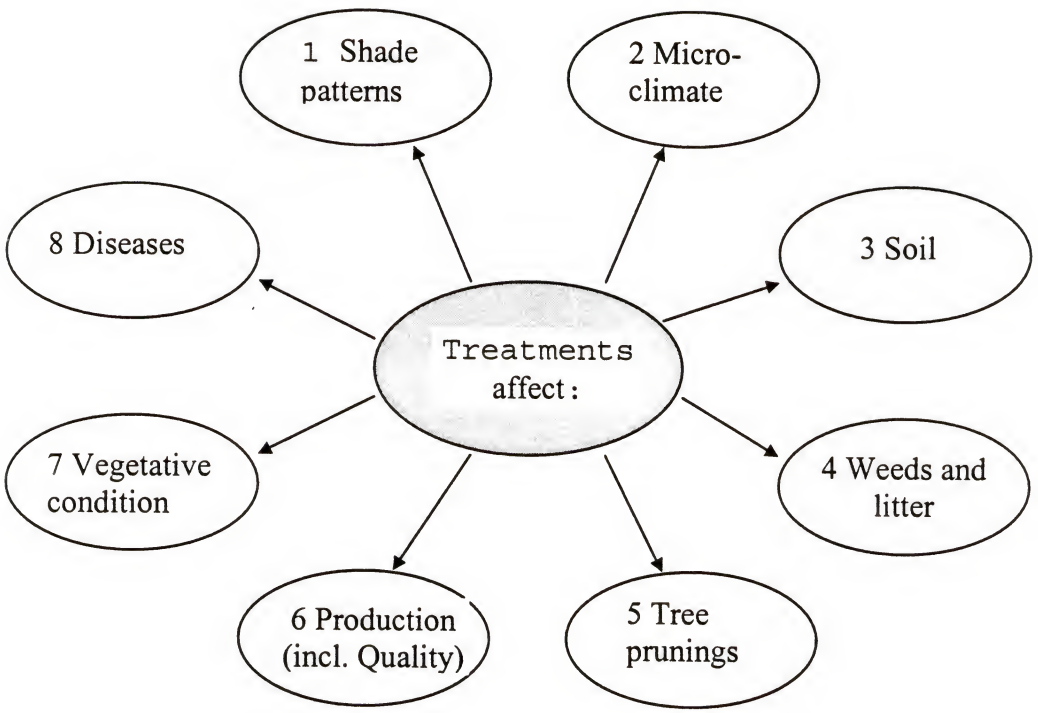


Figure 3-2. Effects of the shade treatments on the coffee environment and on coffee.

All of these factors affect coffee performance and hence are considered part of the coffee environment.

Shade patterns

The mean monthly shade levels were, in ascending order: 0% in sun, 16% under pollarded *Erythrina poeppigiana* (ranging from 3% to 50%), 57% under shadecloth (ranging from 55% to 60%), 58% under open shade (ranging from 46% to 78%), and 86% (range from 77% to 90%) under dense shade of *Erythrina poeppigiana* (Figure 3-3). The pollarding treatment and, slightly less, the open shade treatment exposed the coffee to microclimatic changes at the times of pruning or pollarding.

Microclimate

The microclimate differed strongly between the open and dense shade plots on the one hand and an unshaded (sun) plot on the other. Air temperatures and vapor pressure deficit (VPD) on a sunny day reached their highest levels in the sun plots, exceeding 32°C and 500 Pa, respectively, while both values were substantially lower in the tall shade plots (measurements in the open and dense shade plots did not differ and, hence, were pooled; Figure 3-4). Leaf temperatures differed even more than air temperatures, with sun-exposed leaves exceeding 35°C during several hours

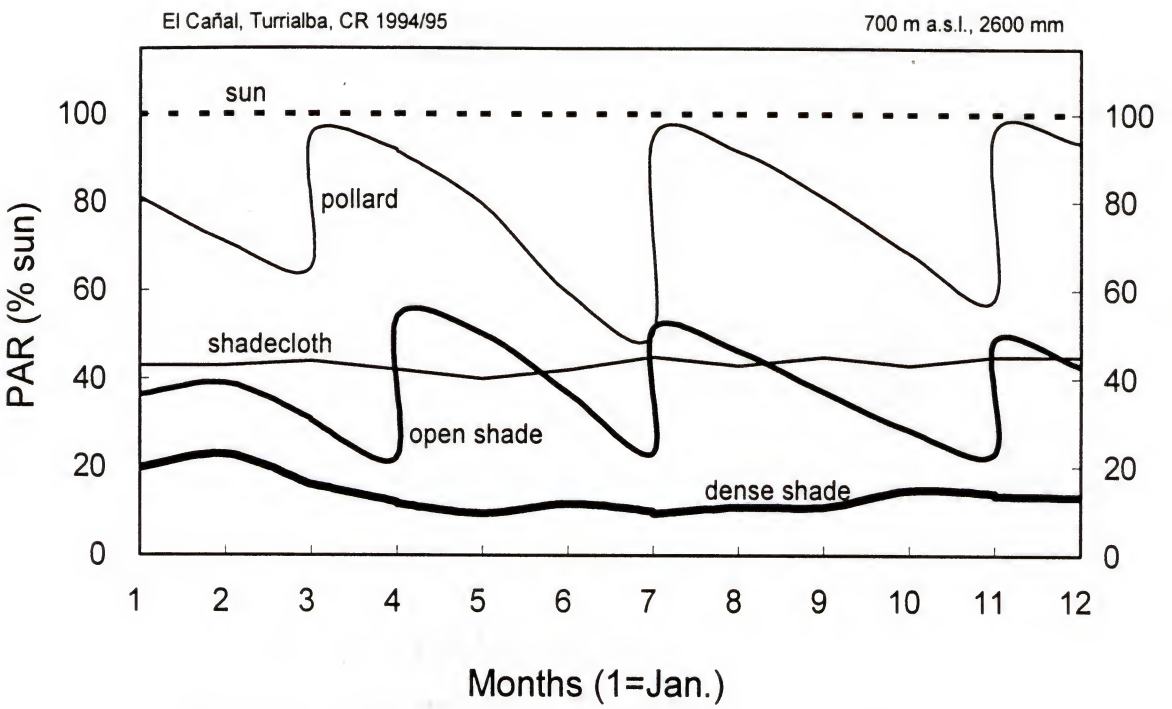


Figure 3-3. Shade patterns, based on monthly PAR measurements (1994-95), imposed by the treatments. The oscillations of "pollard" and "open shade" result from pruning of *Erythrina poeppigiana*.

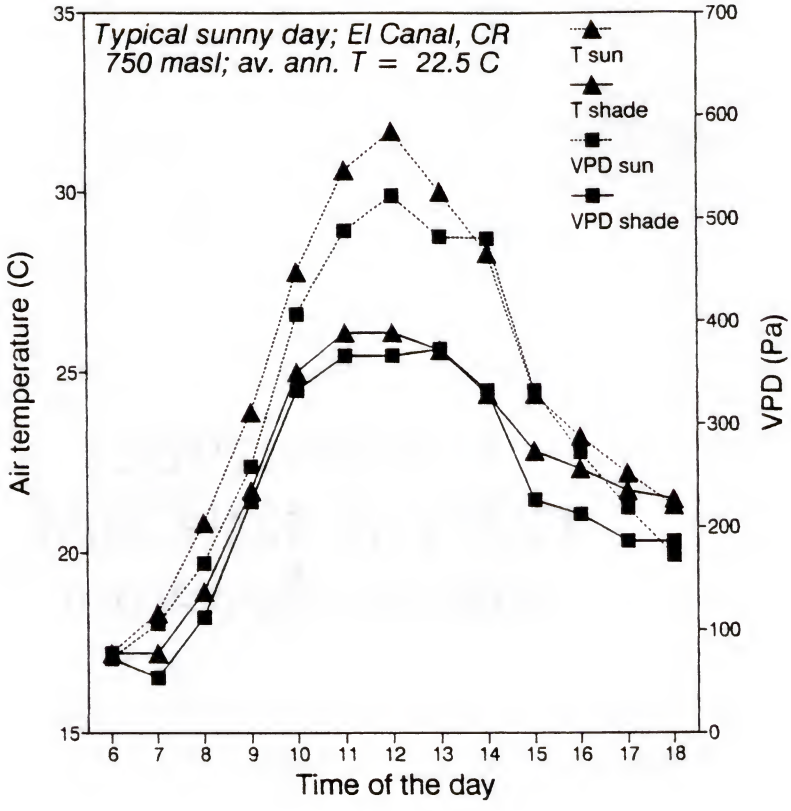


Figure 3-4. Daily course of air temperatures (T_{sun} and T_{shade}) and vapor pressure deficits (VPD_{sun} and VPD_{shade}) on sun-exposed plots versus plots shaded by *Erythrina poeppigiana* (shade level approx. 50%) on a sunny day (23 January 1996).

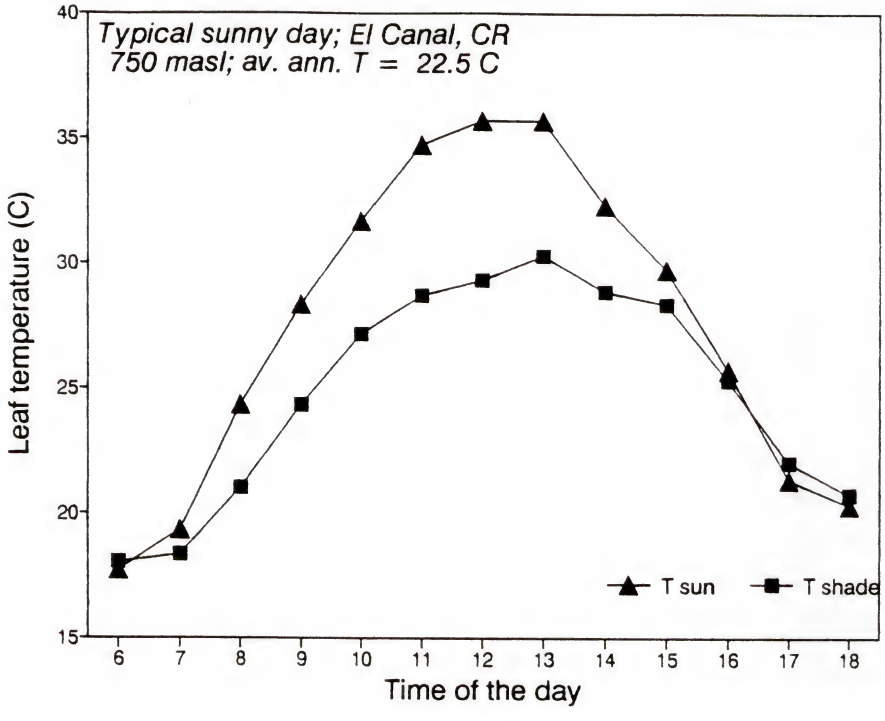


Figure 3-5. Daily course of leaf temperatures on sun-exposed plots (T_{sun}) versus plots shaded by *Erythrina poeppigiana* (T_{shade}; shade level approx. 50%) on a sunny day (23 January 1996).

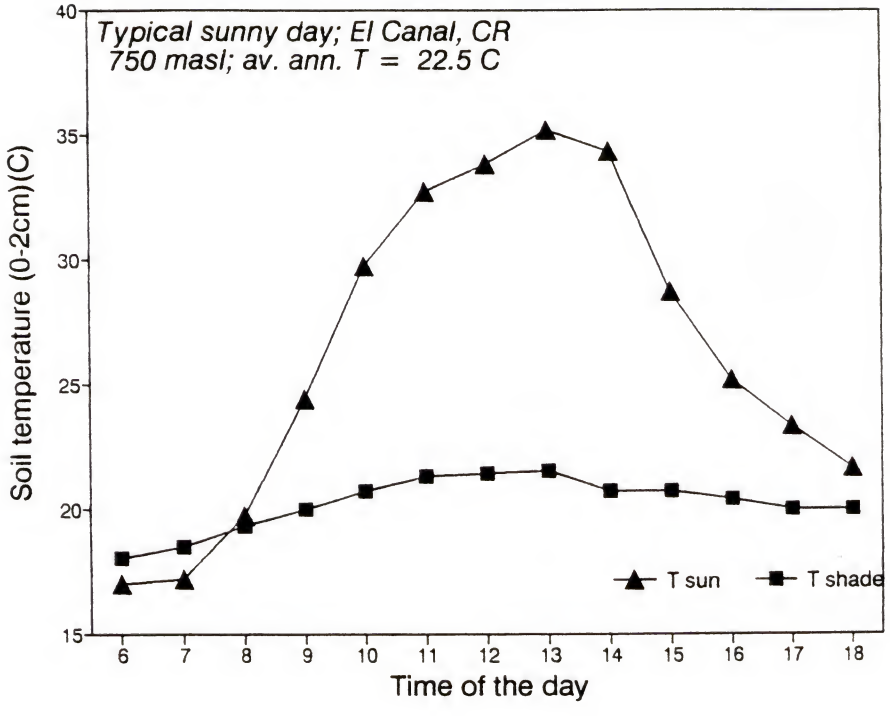


Figure 3-6. Daily course of soil temperatures on sun-exposed plots (T_{sun}) versus plots shaded by *Erythrina poeppigiana* (T_{shade}; shade level approx. 50%) on a sunny day (23 January 1996).

around noon, while shaded leaves never exceeded 30°C (Figure 3-5). The largest differences, however, were found for soil temperatures. Measured at 2 cm depth, a horizon of typically high fine-root activity, soil temperatures of sun-exposed plots exceeded 25°C for roughly half a day centered on noon reaching a maximum of 35°C (Figure 3-6). In contrast, the temperature of shaded and mulch-covered soil was much more stable over the course of the day and never rose above 21°C.

Soil attributes

After four years of managing the shade treatments, the following differences of topsoil attributes were found (although not tested statistically since the composite samples were not replicated) between the dense shade treatment and the sun treatment: organic matter content (OM) was 8.9 % compared to 6.4 % in sun, pH and the concentrations of Ca and Mg were slightly higher, and exchangeable acidity (Al + H) and the concentration of Cu were strongly reduced (Table 3-2).

Weed growth and tree litter

Weed growth, soil cover and tree litter separated the treatments into two groups. The sun and pollarding treatments showed aggressive growth of weeds, predominantly monocotyledons, covering up to 80% of the plot surface and

Table 3-2. Topsoil chemical properties* of shaded plots with litter of *Erythrina poeppigiana* (A_{shade}) and sun-exposed plots (A_{sun}) ("El Cañal").

Horizon	Depth (cm)	O.M. (%)	pH (H_2O)	N tot (%)	P$ mg kg^{-1}	K$ cmol kg^{-1}	Al+H& cmol kg^{-1}
A_{sun}	0-10	6.4	5.0	0.42	9.15	0.28	1.94
A_{shade}	0-10	8.9	5.5	0.49	9.15	0.28	0.22

Horizon	Depth (cm)	Ca& cmol kg^{-1}	Mg& cmol kg^{-1}	Cu$ mg kg^{-1}	Zn$ mg kg^{-1}	Mn$ mg kg^{-1}
A_{sun}	0-10	8.1	2.3	23.5	3.4	43.0
A_{shade}	0-10	10.8	3.1	10.0	2.5	45.0

Horizon	Depth (cm)	CEC# cmol kg^{-1}	Ca# cmol kg^{-1}	Mg# Cmol kg^{-1}	K# cmol kg^{-1}	Na# cmol kg^{-1}	BS %
A_{sun}	0-10	40.0	9.7	2.7	0.68	0.04	32.7
A_{shade}	0-10	37.4	12.7	3.7	0.66	0.05	45.6

* unreplicated composite samples
$ extraction with modified Olsen solution
& extraction with 1N KCl
# extraction with 1N ammonium acetate at pH 7.0

reaching up to 3.6 Mg ha^{-1} of dry weight. This value represents the maximum weed biomass reached before weeding. At the same time, coffee litter in the sun and pollarding treatments was < 0.5 Mg ha^{-1} resulting in < 50% soil cover during large parts of the year (Table 3-3). In contrast, under open and dense shade, weed cover and biomass were minimal while the litter cover was 100% and the biomass from the fallen *Erythrina* leaves (also some coffee foliage but this was a minor component) exceeded 4 Mg ha^{-1} (Table 3-3).

Table 3-3. Soil cover and biomass of weeds and tree litter in the four shade treatments in El Cañal, Turrialba, Costa Rica (n = 5).

Parameter	Sun	Pollard	Open shade	Dense shade
Weed cover (%)	80	65	< 5	< 5
Weed biomass (Mg ha^{-1})	3.6	2.6	< 0.1	< 0.1
Litter cover (%)	< 30	< 50	100	100
Litter (Mg ha^{-1})	< 0.5	< 0.5	4.0	4.8

Pruning biomass and nutrient inputs

Both fresh prunings (leaves and non-lignified shoots) as well as senesced leaves were very high in nutrients (Table 3-4). Freshly abscised leaves retained surprisingly high nutrient concentrations, particularly of N (3.0%) and P (0.19%). The nutrient concentrations of the pruned leaves were used to calculate the nutrient contributions of the foliar portions of the pruning residues (Table 3-5).

Table 3-4. Nutrient concentrations in pruning residues and litterfall of *Erythrina poeppigiana* sampled in 12/95 (unreplicated composite samples).

NUTRIENT	Active leaves and non-lignified shoots	Abscised leaves[&]
N (%)	4.69	2.98
P (%)	0.29	0.19
K (%)	1.46	1.14
Ca (%)	1.46	1.86
Mg (%)	0.32	0.30
Zn (mg kg^{-1})	30	32
Mn (mg kg^{-1})	60	76
Cu (mg kg^{-1})	8	12

[&] leaves that had fallen on the day of sampling

Table 3-5. Nutrient inputs per year from fertilization and pruning residues[@] from *Erythrina poeppigiana*, and nutrient export in 7.5 Mg of fresh ripe coffee berries.

INPUT/OUTPUT VIA	OM[@]	N	P	K	Ca	Mg
	----------kg ha^{-1} yr^{-1}----------					
INPUTS						
(1) Pollarding[#]	1241	58	3.6	18	18	4.0
(2) Open shade (selective pruning)[#]	2277	106	6.6	33	33	7.3
(3) Commercial fertilization[$]	---	219	31.5	94.5	100	37.8
OUTPUTS						
(4) Harvested coffee (7.5 Mg fresh weight ≅ 30 sacks green coffee @ 46 kg)	1500	-27	-1.5	-27	-3.6	-1.5
BALANCE for pollarding (1+3-4)	---	250	33.6	85.5	114.4	40.3
BALANCE for open shade (2+3-4)	---	298	36.6	100	119.4	43.6

[@] Organic matter inputs from tree pruning (dry weight of leaves and green non-lignified shoots); does not include litter fall, branches, stems, roots, or coffee residues.
[#] Calculated for 156 trees per hectare (8 X 8 m spacing).
[$] Standard recommendation per hectare and year: 2 x 315 kg of complete fertilizer (18-5-15-6-2; N-P-K-Mg-B) + 315 kg NH_4NO_3 + 250 kg $CaCO_3$.

During the first year of the experiments (1994), the selective pruning of the tall *Erythrina* in the open shade treatment yielded substantially more biomass and nutrients than tree pollarding. The totals for the three pruning or pollarding operations during the first year, calculated for 156 trees per hectare (8 X 8 m spacing), are contrasted with the nutrient inputs from industrial fertilization in Table 3-5.

Additional biomass contributions via natural leaf litter fall (not quantified) increased the foliar biomass inputs even further for the open and dense shade treatments, but not for the pollarding treatment where the maximum leaf age was about 4 months (at three pollardings per year). The balance in Table 3-5 shows a positive nutrient balance irrespective of the tree pruning system (i.e., pollarding or open shade). The high fertilizer inputs render the nutrient inputs (not the OM inputs, though) via tree prunings of secondary importance.

Coffee Responses

This section consists of three parts: production, vigor/vegetative condition, and disease infection. Coffee quality is treated in Chapter 4.

Production across environments

Plotting the data of potential production (PP; harvest 1995/96) for each of the four shade treatments at nine sites against the average PP of the treatments at each site (= "environmental index EI"), a standard procedure of adaptability analysis *sensu* Hildebrand and Russell (1996), reveals that the sun and pollarding treatments were strongly benefitted by better environments (Figure 3-7A); the differences between these and the open and dense shade treatments increased with EI. At EI below about 20, i.e. at less than 2000 fruits per plant, the differences among the treatments became relatively small. Considering that the ultimate variable of interest is not the number of fruits set (PP), but rather the weight and size of the acutally harvested berries, both of which are strongly favored by shade (cf. Chapter 4), the yield differences of quality fruit among the four treatments would disappear at EI below 20. The relatively smaller slopes of the regression lines of the open shade and dense shade treatments indicate higher stability across environments than the other two treatments (Figure 3-7A). Because all experimental plots had been established on commercial plantations with high fertilizer inputs and similar soil conditions (visual check in soil pits), soil chemical differences among the nine sites were

probably too small to account for the differences between the environments with EI > 20 and the others. The major environmental differences among the sites were elevation (700 m a.s.l. to 1000 m a.s.l.) and slope (0% to 35%). Considering that the elevation of the nine sites differed by only 300 m, a value relatively small compared to the total range of elevations suitable for coffee in Costa Rica (500 m a.s.l. to 1600 m a.s.l.), elevation probably also played only a minor role to separate the nine environments. Plotting the EI as a function of slope shows that production decreased with increasing slope (Figure 3-7B). However, the small number of environments and having only three environments on slopes handicaps this interpretation seriously. Therefore, no attempt was made to interpret the treatment behavior of Figure 3-7 further. More environments would be needed to verify if slope really has any significant effect. Also, the biennial production cycle of coffee, which could have been out of phase among the sites, limits the value of one-year evaluations (Wrigley 1988). Nevertheless, the main tendency of increasing treatment differences with site quality are consistent with observations by other workers (Wrigley 1988) and can be

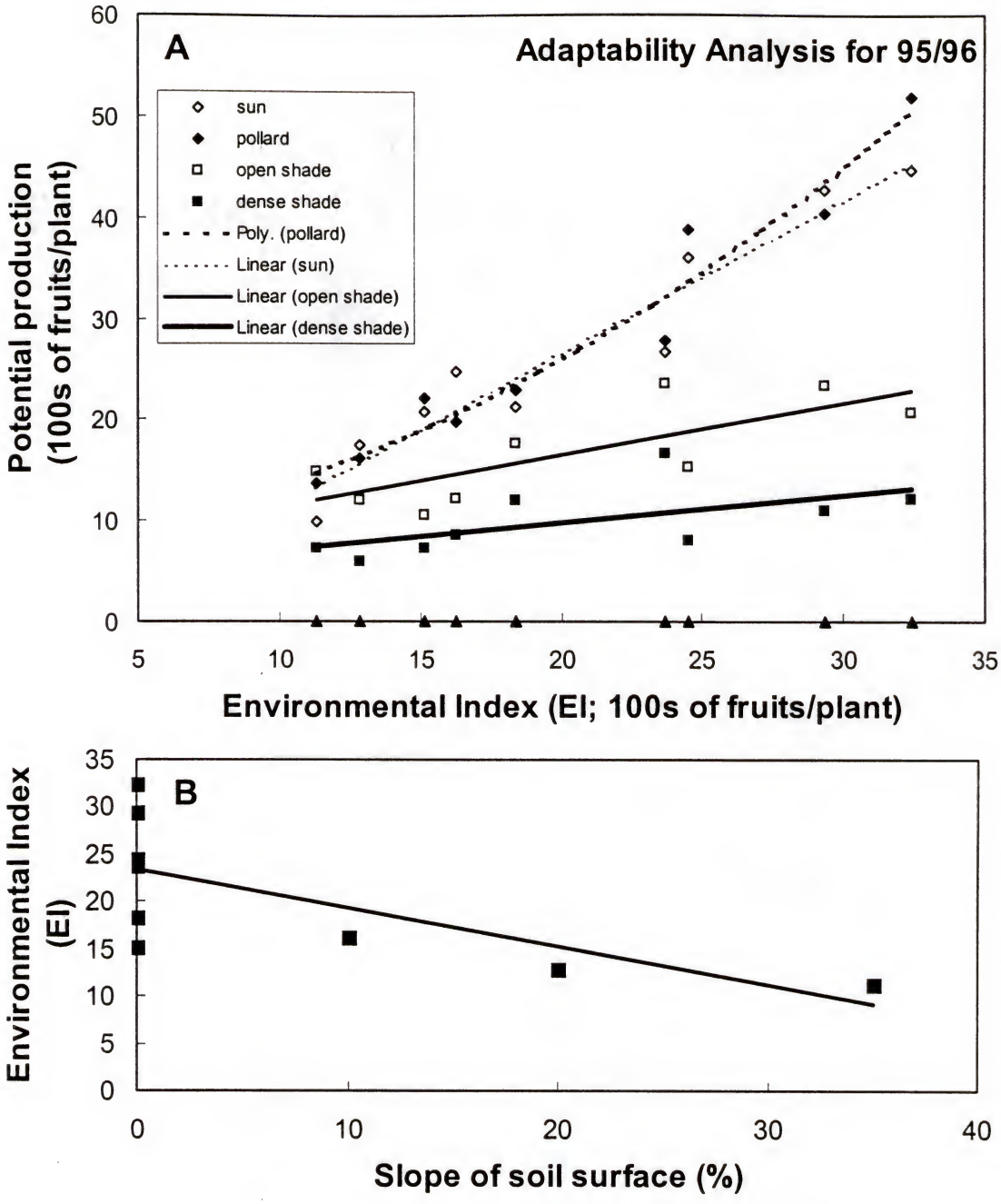


Figure 3-7. A. Adaptability analysis for shade treatments at nine sites in Turrialba, Costa Rica. The environmental index is the average potential production of all treatments at each site. B. EI of each site as a function of slope.

explained both at physiological and ecological levels (cf. Fournier 1988; Carvajal 1984 and discussion below).

Production in the "Central Experiment"

For both varieties studied, Caturra and Catimor 5175, fruit maturation occurred earlier for fruits exposed to higher light levels in the sun and pollarding treatments than under the shade treatments (Figure 3-8). However, the speed of maturation for the bulk of the harvest totals (indicated by the slope of the cumulative harvest curves between days 60 and 100) and the total duration of harvest were similar for the sun, pollard and dense shade treatments. Surprisingly, the open shade and the shadecloth treatments had higher maturation rates than the other treatments between the days 60 and 100. The total harvest period did not differ among treatments because the delay of maturation of shade-grown berries (about 30 to 40 days relative to sun) was balanced by a similar period of time needed to complete the harvest.

For both coffee varieties, the yields of "quality berries" averaged over four years differed surprisingly little among treatments (Figure 3-9) considering the large differences in shading. Only the production of Caturra differed significantly among the treatments.

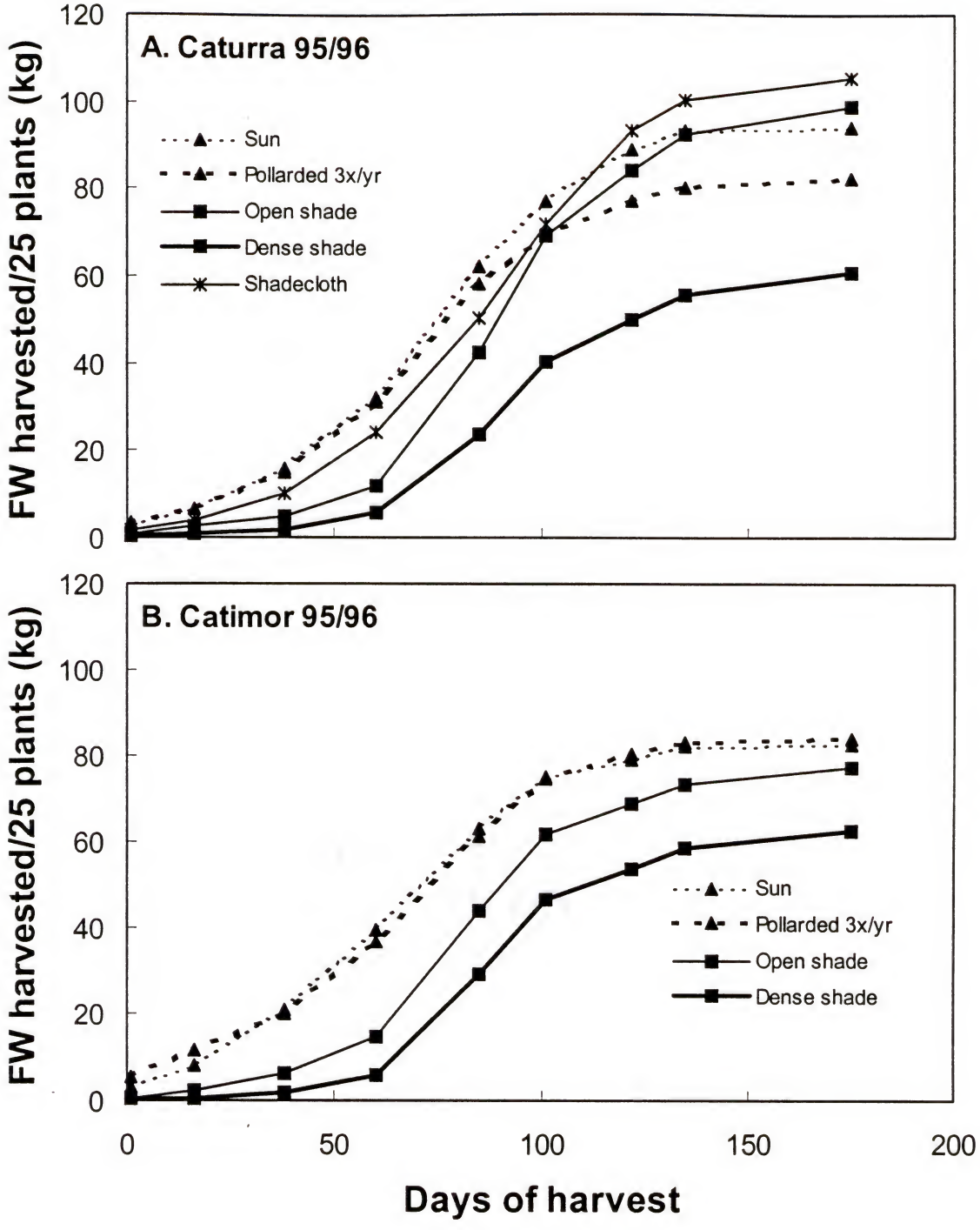


Figure 3-8. Cumulative harvest for 1995/96 (total production) of *Coffea arabica* var. Caturra (A) and Catimor 5175 (B) under different levels of shade in "El Cañal", Turrialba, Costa Rica.

For both varieties, the sun and pollarding treatments produced similar amounts of quality fruits. Open and dense tree shade reduced production relative to sun by 15% and 37%, respectively, for Caturra, and by 3% and 12%, respectively, for Catimor 5175 (Figure 3-9). Although the unreplicated shadecloth treatment was not included in the statistical analysis, it apparently produced similarly high amounts of quality fruit as the sun and pollarding treatments during the three years that flowering was affected by the shadecloth[1].

Over the four years studied, the yearly harvest totals demonstrated the typical biennial cycle of coffee production (Figure 3-10). Both varieties went through the same cycle with a maximum production in 1995/96 followed by a minimum production in 1996/97 and recuperation in 1997/98.

The differences in the quantities of quality fruits, however, do not reflect all of the physiological effort of each coffee plant. In addition to quality fruits, the plant has to expend resources for the deformed and infected fruits (rejects) although they are of no benefit to the producer.

---

[1] In March 1996, after flowering and fruit set for the harvest 1996/97, the shadcloth was stolen. From thereon the plot was exposed to full sun but continued to be harvested also for the next two years, accounting for the changed light levels for the interpretation (see below).

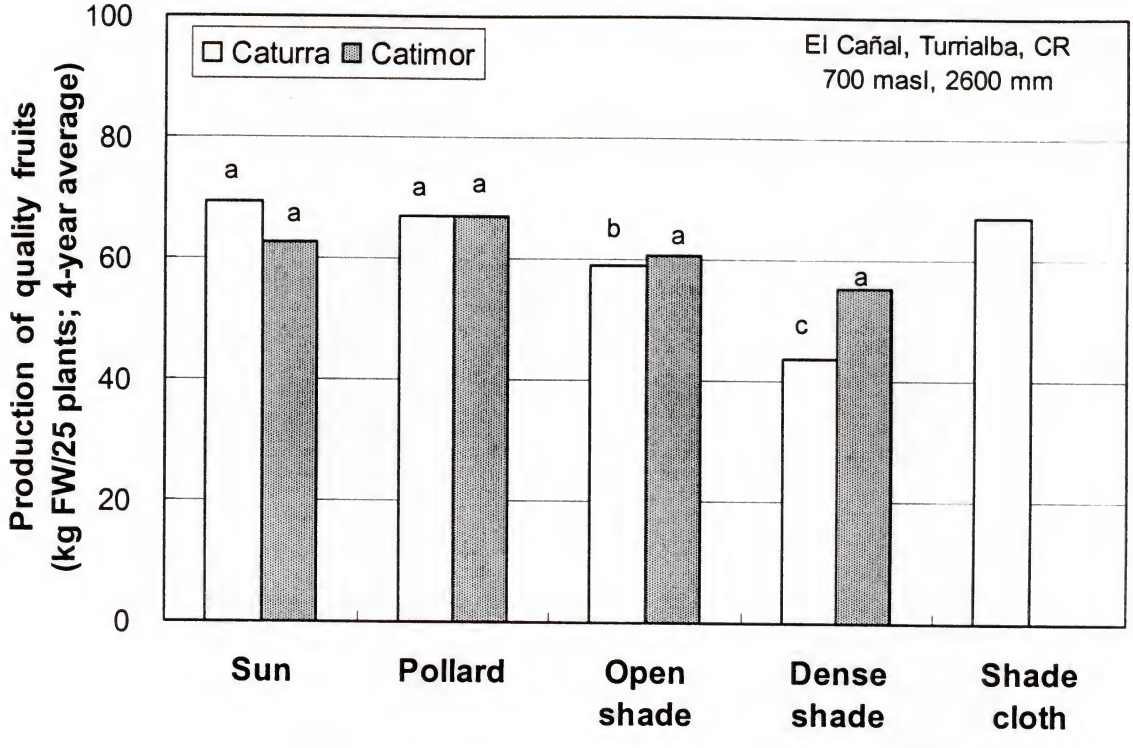


Figure 3-9. Production of "quality fruits" of *Coffea arabica* vars. Caturra and Catimor 5175 for the five shade treatments (3-yr average for unreplicated shadecloth; 4-yr averages for others; FW = fresh weight). Within varieties, treatments with the same letter did not differ significantly (Duncan @ α=0.05).

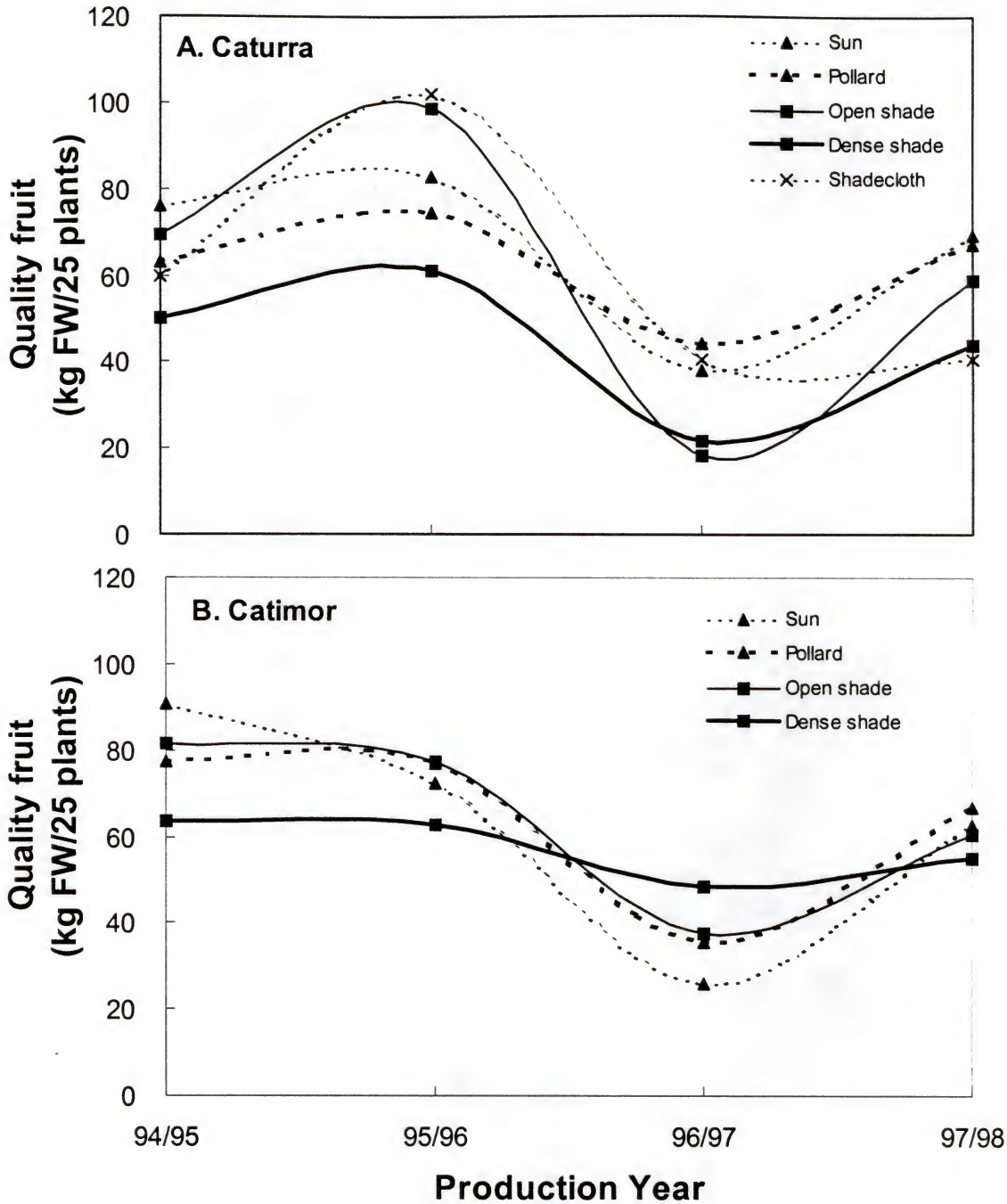


Figure 3-10. Harvest fluctuations (smoothed curves) over four years for *Coffea arabica* vars. Caturra and Catimor 5175 under different shade treatments (shadecloth was removed in 03/96) in "El Cañal", Turrialba, Costa Rica (FW = fresh weight).

Such rejects appear in two ways: as coffee berries that fall off the plant prior to, or during, the harvests, and as rejects that are harvested but that will later be separated in the processing plant.

The numbers of fallen fruits under coffee plants were significantly higher, consistent for all three sites sampled (E5, E6, and E9; cf. Table 2-2), in the sun and pollarding treatments than in the open and dense shade treatments (Figure 3-11). The benefits of shade were also reflected in the proportion of rejects in each treatment: while the harvested berries from sun and pollarding plots included 10% and 7%, respectively, of rejects during the first two years, there were no rejects under open or dense shade (Figure 3-12); all the fruits harvested under shade were well-formed and healthy. The shadecloth treatment had 3% of rejects (not shown in graph since this treatment was not replicated).

The fallen fruits and the rejects are responsible for potentially large differences between the evaluation of potential production based on a count or estimation of the total number of fruits on each plant, on the one hand, and the actual harvest of "quality fruits" on the other. Such differences can greatly influence management decisions (see discussion below).

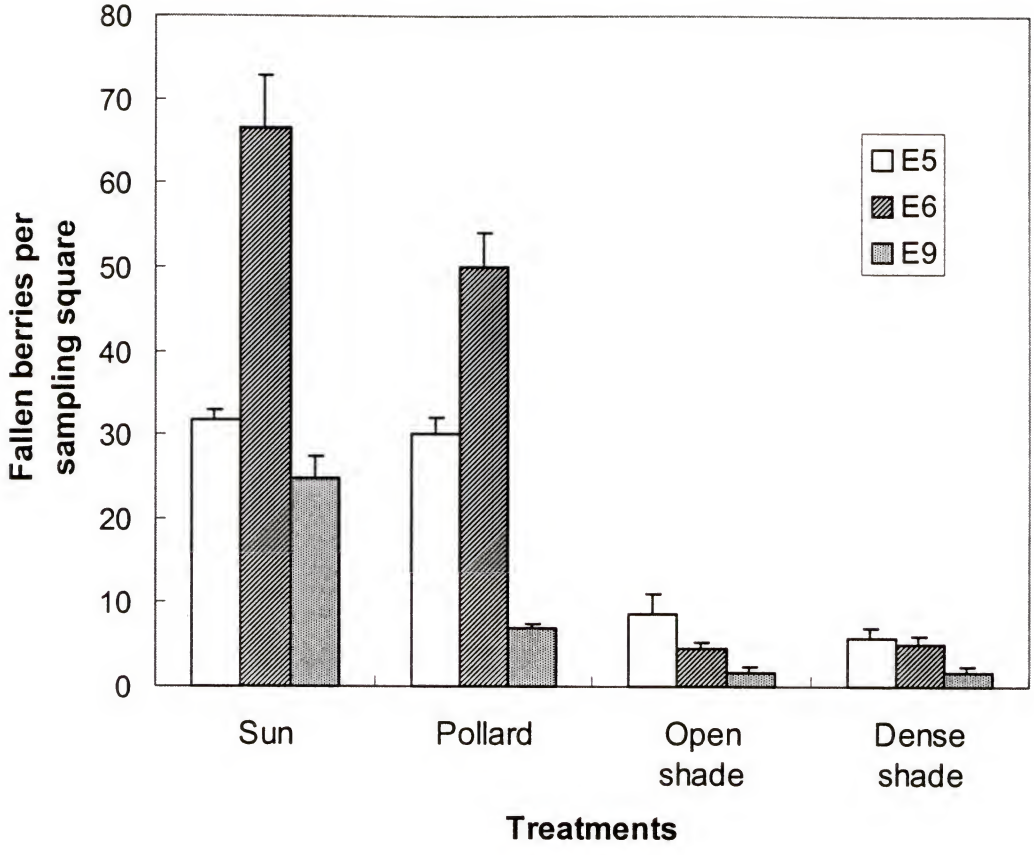


Figure 3-11. Number of fallen coffee berries (mean ± SE; n = 5) on the soil per sampling square of 0.4 X 0.4 m at three sites (E5, E6, E9).

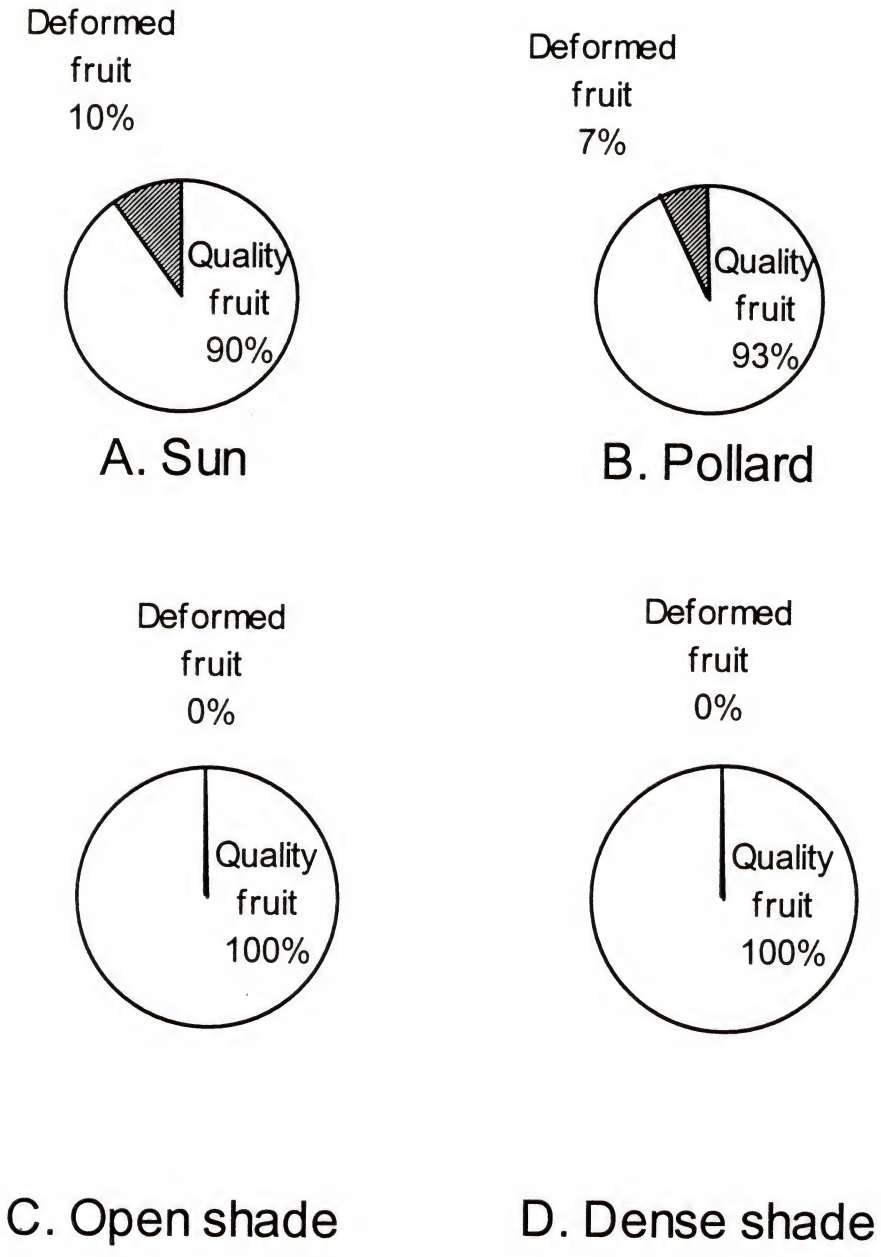


Figure 3-12. Mean (n = 8) percentage of fruit rejects for *Coffea arabica* under four shade treatments in "El Cañal", Turrialba, Costa Rica (700 m a.s.l., 2600 mm; harvests 1994/95 and 1995/96).

Figure 3-13 illustrates how such differences among different production measures can modify the conclusions about the light response of coffee. The data shown are from the four experiments in "El Cañal" for the harvest 1995/96. The top panel shows the total number of fruits per plant (TF in Equation 3-1), a measure of "potential production," as a function of the yearly average of PAR available to the coffee plants (Figure 3-13A). The best regression is a straight line which suggests a strong increase of production with increasing light availability. However, when coffee production is assessed as actual harvest (QF + RF in Equation 3-1), the fraction of berries shed by the plants prior to or during harvest is not included in the assessment (Figure 3-13B). Since the sun and pollarding plots with higher light exposure had the largest fruit losses (cf. Figure 3-11), resulting in a decrease of harvested fruits relative to the open and dense shade treatments, the relationship between berry weight harvested and PAR becomes curved (Figure 3-13B).

Subtracting furthermore the rejects from the harvested berries, again affecting only the sun and pollarding plots, and plotting the resultant quantities of quality fruit as a function of average PAR makes the quadratic relationship even more pronounced (Figure 3-13C and discussion below).

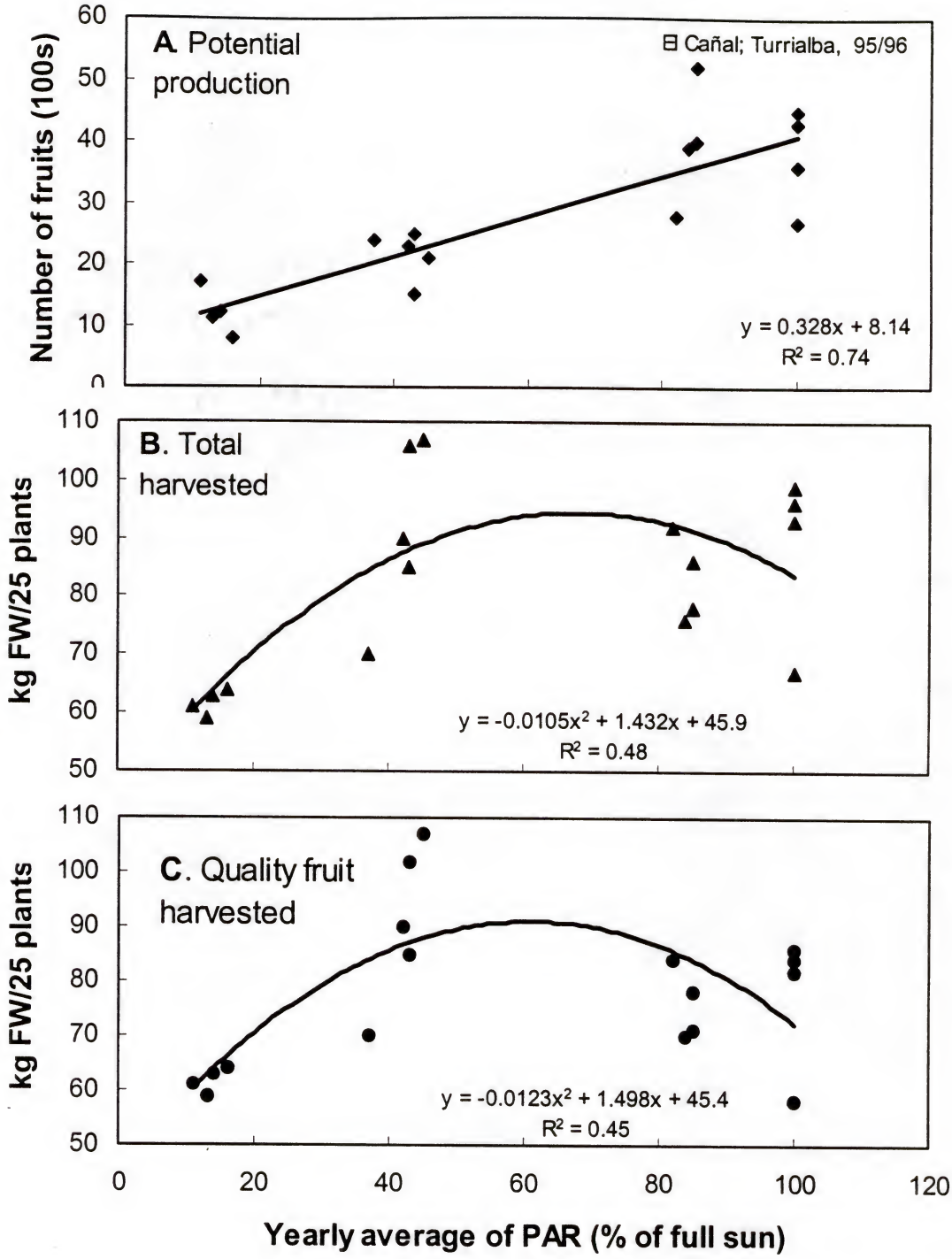


Figure 3-13. Regressions of estimated number of fruits (= potential production; A), total yield (B), and yield of quality fruits (C) as functions of the average annual PAR-levels. The dots represent the estimated or harvested yields of the 17 plots in El Cañal for 1995/96 (FW = fresh weight).

The resulting regression suggests a "window" of optimum PAR-levels between about 40% to 80% PAR, equivalent to 20% to 60% shade.

Vegetative condition

The coffee plants under the open and dense shade treatments were significantly taller than the plants in the sun and pollarding treatments (Figure 3-14A). Crown diameter was less affected by the treatments, and only the plants under dense shade had significantly higher diameters than those in the sun or pollarding plots (Figure 3-14B). Foliation index as a relative measure of leaf retention in the last quarter of the harvest period, i.e. when the plants are typically most stressed (Müller 1995), was significantly higher under the open and dense shade treatments than in sun or pollarding plots (Figure 3-14C). Comparing the two varieties, plants of Catimor 5175 had a larger crown diameter but less foliation in the sun and pollarding plots than Caturra (Figure 3-14B, C). Under open and dense shade, Catimor 5175 had slightly larger crown diameters and higher foliation indices than Caturra.

Deficiencies and diseases

Foliar deficiencies were only apparent in the sun and pollarding treatments (Figure 3-15A) where they may be

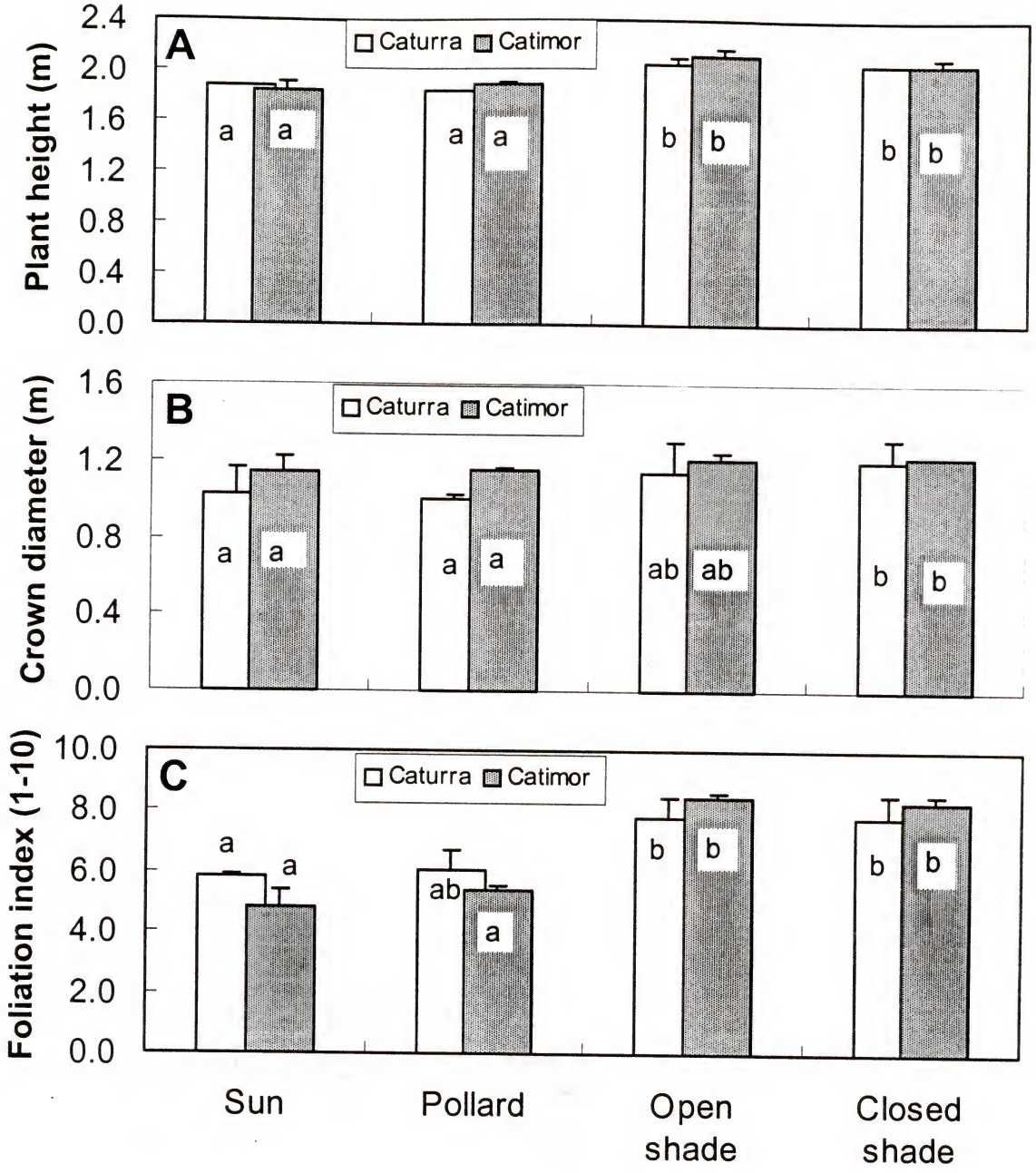


Figure 3-14. Vegetative condition of *Coffea arabica* var. Caturra and Catimor during the fourth quarter of the harvest period 1995/96 under four shading treatments in "El Cañal", Turrialba, Costa Rica (means ± SE; n = 2). Within varieties, means with the same letter are not significantly different at $\alpha \leq 0.05$.

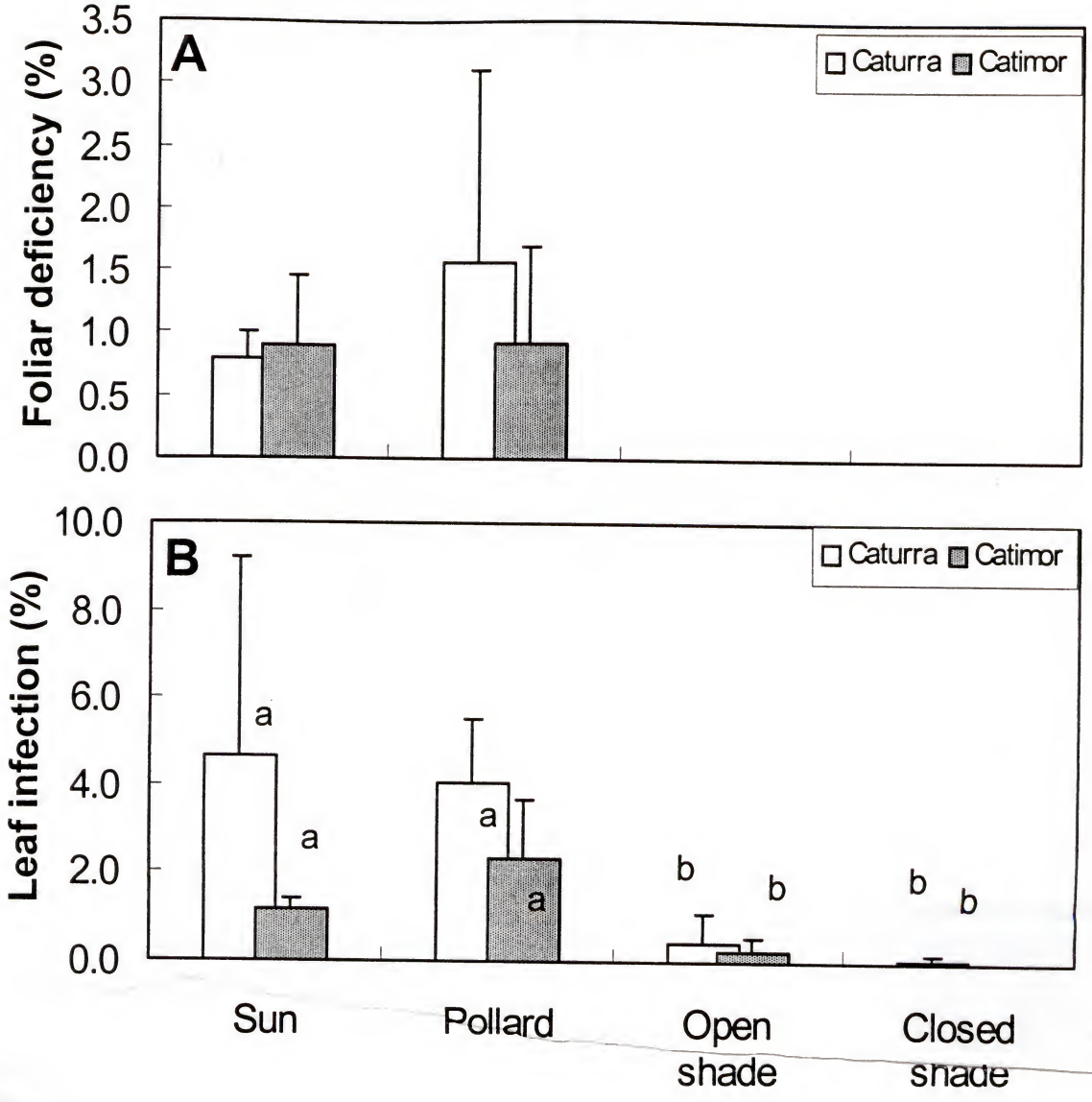


Figure 3-15. Leaf deficiencies (visual scoring) and infection of *Coffea arabica* var. Caturra and Catimor during the fourth quarter of the harvest period 1995/96 under four shading treatments in "El Cañal", Turrialba, Costa Rica (means ± SE). Within varieties, means with the same letter are not significantly different (t-test @ $\alpha \leq 0.05$; n = 2).

Table 3-6. Nutrient concentrations (means, n = 2) in sun-exposed and shaded leaves[&] of *Coffea arabica* L, and significance levels for t-tests within years.

	DECEMBER 1995			NOVEMBER 1997		
NUTRIENT	SUN	SHADE	P > t	SUN	SHADE	P > t
N (mg g^{-1})	25.65	25.55	ns	24.50	26.55	ns
p (mg g^{-1})	1.20	1.10	ns	1.20	1.30	ns
K (mg g^{-1})	11.20	13.90	0.16	12.15	19.70	0.01
Ca (mg g^{-1})	16.20	16.80	ns	19.15	19.55	ns
Mg (mg g^{-1})	6.30	5.00	ns	7.45	6.00	0.16
Zn (mg kg^{-1})	14.0	18.0	ns	8.9	16.4	0.00
Mn (mg kg^{-1})	479	396	ns	462	473	ns
Cu (mg kg^{-1})	12	12	ns	9.9	19.4	0.06
B (mg kg^{-1})	nd	nd		73.1	77.4	ns

[&]4th pair of fully developed leaves from the apical meristem, taken from branches in the upper half of the coffee bushes.

interpreted as stress symptoms (Müller 1995; Marschner 1991). While most foliar nutrient concentrations were in their "normal" range, the concentrations of P and K in 1995 were close to or below the deficiency levels of 0.12 % P and 1.5% K given by Müller (1959)(Table 3-6). The largest differences between sun and shade leaves were found for K with 1.39% in shade vs. 1.12% in sun in 12/95, and 1.97% in shade vs. 1.22% in sun in 11/97. Also the Zn concentrations in 1997 were significantly higher in shade than in sun.

For both coffee varieties, leaf infections were only pronounced in the sun and pollarding treatments while the open and dense shade plots showed only minimal levels (Figure 3-15B). The most important disease was *Cercospora coffeicola,* followed by *Colletotrichum* spp. and *Hemileia vastatrix*.

Discussion

Environmental Modification

Shade patterns

The annual PAR-transmission curves (Figure 3-3) illustrate the shading patterns ranging from shade that is homogeneous in space and time at three levels of shade intensity (sun, shadecloth, closed shade) to spatially and temporally variable shade at two levels (pollard, open

shade). The large fluctuations of shading (50% to 98%) and the relatively high PAR-transmission (84% as a yearly average) of the pollarding treatment are typical for many of the coffee systems in Costa Rica classified as "shade systems." In contrast, the selective pruning in the "open shade" treatment (which left, on average, three main branches of the tree untouched) reduced both PAR-transmission (yearly average of 42%) and the shade fluctuations (22% to 54%) markedly. The fluctuations under open shade were even less during the third and fourth years of the study because only minor pruning was necessary to maintain the intermediate shade level; after the first two years of selective pruning, the trees had a crown architecture with widely spaced gaps that did not allow complete canopy closure as before.

The dense shade treatment allowed the tree crowns to mature and enter into the adult phenological cycle of *Erythrina* which sheds most or all of its leaves at flowering during the drier months of January through March. The peak of PAR-transmission for dense shade in Figure 3-3 corresponded to leaf fall of the three- to four-year-old tree crowns of Erythrina. The slight variations in PAR-transmission under shadecloth in Figure 3-3 reflected measurement errors and, possibly, slight changes in the

atmospheric water content although all measurements were taken on clear sunny days.

Microclimate and implications for coffee physiology

The differences of air and leaf temperatures between shaded and unshaded plots (Figure 3-4, Figure 3-5) were within the ranges found by Butler (1977) and Barradas and Fanjul (1986). The latter authors reported an average difference of 5.4°C for the maximum temperatures between coffee plots with and without shade. The air temperatures to which the unshaded plants were exposed during several hours around noon were probably high enough to reduce photosynthesis. Studies of Kumar and Tieszen (1980) and Nunes et al. (1968) showed decreased photosynthesis at temperatures above 25°C and Nutman (1937) documented mid-day stomatal closure for coffee in Kenya. In contrast, since the shaded leaves never exceeded this critical temperature by more than 5°C, not even during the noon hours on sunny days (Figure 3-4, Figure 3-5), it is likely that their photosynthetic rates were not limited by these conditions.

The markedly higher vapor pressure deficits in the sun (Figure 3-4), similar to the 0.2 kPa difference found by Barradas and Fanjul (1986), probably contributed to higher water losses of the sun-exposed leaves (observed as

"wilting" leaves during periods of high insolation). This response, together with reduced water use efficiency at temperatures above 25°C (Nunes *et al.* 1968), may have led to a higher disposition of sun-exposed leaves for mid-day stomatal closure, contributing to a reduction of photosynthesis (Nutman 1937; Nobel 1991). Since leaf retention was markedly reduced for sun-exposed plants (Figure 3-14), self-shading within and between individual plants, which could potentially buffer the extremes, was decreased. Therefore it is likely that heat stress was not limited to the distal sun-exposed leaves of unshaded coffee bushes, but that it affected also many of their interior leaves.

Since the sun-exposed soil temperatures at 2 cm depth exceeded 26°C (the optimum temperature for root growth; Franco 1958) for more than five hours per day (Figure 3-6), it is likely that root growth close to the soil surface, a zone of great importance for coffee fine roots (Aranguren et al. 1982; Wrigley 1988), was severely hampered. Superficial excavations and visual assessments (not quantified) confirmed the absence of fine roots in this zone of the sun plots but not in the shaded plots. In the shaded plots, the soil temperatures stayed around 20°C, a temperature highly

favorable to root growth and function (Franco 1958; Bowen 1991; McMichael and Burke 1996).

Soil attributes

The high concentrations of soil organic matter (SOM), irrespective of treatments, can be explained largely by the reduced SOM mineralization in soils with andic properties (Bornemisza 1982; Van Wambeke 1992). The increased SOM under shade is likely the result of the higher litter input under *Erythrina poeppigiana,* a result also described for similar systems elsewhere (Beer 1988; Fassbender et al. 1991; Fassbender 1993). This higher litter input under shade, covering 100% of the soil surface with litter (Table 3-3), may also be responsible for the much lower Cu concentrations in the topsoil under shade. Here, the closed litter layer (compared to < 30% of the soil surface covered by litter in the sun treatment) may have intercepted most the Cu depositions during the applications of Cu as a fungicide.

Reduced soil acidity, as well as the increased concentrations of Ca and Mg under shade indicate improved topsoil conditions under *Erythrina poeppigiana*. However, since the management regime of the commercial plantation in which the experiments were located prescribed yearly applications of lime (equal quantities on all plots/treatments), the higher values of Ca and Mg cannot be

attributed solely to the trees. Rather, the trees affected nutrient cycling probably indirectly via their contributions to SOM (Young 1989, 1997) and via microclimatic moderation which in turn affects rates of decomposition of SOM and rates of nutrient cycling (Jordan 1985; Fassbender 1993). However, since the nutrient levels in the topsoil were affected strongly by fertilization, differences between them should not be overinterpreted. Furthermore, while the intensity of soil sampling (unreplicated composite samples) permitted an overall characterization of the soils, it was not designed to generate statistically testable information that would permit detailed interpretations beyond the major tendencies of increased SOM and reduced soil acidity under shade.

Weed growth and tree litter

The large differences in weed growth as a function of shade agreed with the work of Knipschild (1997), Goldberg and Kigel (1986) and Jimenez (1979) who all described much greater weed biomass and different species composition in unshaded vs. shaded coffee plantations. However, the weed biomass of 3.6 Mg ha^{-1} observed here in sun plots was roughly one third of that reported by Goldberg and Kigel (1986) from Mexican coffee plantations after removal of shade trees. The main reason for this large difference in

weed biomass may be the different timespan for weed growth: 15 months after tree removal in Mexico vs. about 4 months after the last herbicide application in this study.

There are several possible impacts of greater weed growth on coffee. Apart from temporary nutrient storage in the weed biomass, probably not of great consequences in high-input systems such as the one studied here (Knipschild 1997), weeds may exert their greatest effect via water competition during dry spells (Friessleben et al. 1991). However, given the absence of a marked dry season, it is possible that also this effect is of relatively little importance in Turrialba. Nevertheless, the vigorous weed development in the "open" systems requires weed control for easy access to the fields, to prevent shading of the coffee by weeds, and to facilitate the normal management practices such as pruning, fertilization and harvesting. The economic and ecological implications of weed control will be discussed in a separate section on management costs.

Pruning biomass and nutrient inputs

Although the foliar nutrient levels of *Erythrina* in this study (Table 3-4) fall well within the ranges of foliar nutrient levels summarized for broad-leaved tropical trees by Drechsel and Zech (1991), they exceeded the values given by Russo and Budowski (1986) substantially, particularly for

N (4.7% vs. 3.6%) and P (2.9% vs. 1.9%). Possibly, this difference may have been due to the high levels of mineral fertilization (Table 3-5) in the experiments, and the ability of the ecosystem to retain a higher proportion of N and P than the more easily leached K (Fassbender 1993; Jordan 1985).

The nutrient concentrations in the senesced tree leaves (3.0% N and 0.19% P) were much higher, for N by a factor of two, than the average values reported by Killingbeck (1996). Unfortunately, the data set of Killingbeck did not include *Erythrina* or a species of similar characteristics. The high nutrient concentrations in senesced leaves suggest that *Erythrina* has a very low capacity to retranslocate nutrients prior to leaf abscission, an attribute called resorption capacity by Killingbeck (1996). Having low resorption capacity might be desirable where trees are expected to boost nutrient turnover and input. However, it needs to be studied to what extent the high fertilization rates in this study might have been responsible for this low efficiency.

The data on biomass and nutrient inputs under pollarded vs. selectively pruned *Erythrina* trees (Table 3-5) show the potential importance of the trees for nutrient cycling. The nutrient contributions via the non-lignified pruning residues alone exceeded the nutrient export in 7.5 Mg of

fresh coffee berries (approximately the national average production per hectare for Costa Rica (ICAFE-MAG 1989) by at least a factor of two (Table 3-5). While the biomass and nutrient contributions of trees in this study seem much smaller (by a factor of three, for open shade, to five, for pollarding) than those reported by Russo and Budowski (1986), it has to be considered that neither the lignified pruning residues nor the natural litterfall were quantified in the present study. Adding their nutrient contents, and increasing the number of trees per hectare to tree densities described by other authors (e.g., Beer 1988), would make the values fall into the range of tree litter inputs in coffee plantations (3.1 to 22.8 Mg ha^{-1}) summarized by Beer (1988).

Coffee Responses

Production

The four-year harvest totals gave three surprising results: first, the pollarding treatment did not exceed the sun treatment in yield despite the organic matter inputs and nutrient cycling effects of the *Erythrina* (Figure 3-9). Second, the dense shade treatment produced more coffee than expected (Figure 3-9) despite a shade level (ranging from 77% to 90% during the first two years) considered excessive by local coffee experts. And third, the homogeneous reduction of PAR, both in space and time, by 55% to 60%

under shadecloth apparently did not reduce coffee flowering and production. These unexpectedly high yields, despite high or even "excessive" shade, may illustrate that even the "modern" varieties maintain a relatively strong adaptation or tolerance to shade.

The low production in 1996/97 was probably due to two principal factors: first, the high productions in previous years resulted in plants that required strong pruning after the harvest 1995/96. And, second, it is likely that the extremely high rainfall of 770 mm in February 1996 (cf. Figure 2-2) contributed to reduced flowering and, consequently, reduced production in 1996/97. While the cycling was relatively synchronous among treatments for Caturra, except for the open shade treatment, increasing shade intensity clearly reduced the fluctuation for Catimor (Figure 3-10B). The unexpectedly strong cycling of open shade and the relatively low value of dense shade for Caturra in 1996/97 resulted in large part from an unnecessarily intense (in the open and dense shade plots) pruning of the coffee after the 1995/96 harvest which reduced the production capacity particularly of the open shade plants unduly. Since the adjustments to correct for the excessive pruning only accounted for plants which had all branches removed, but not for those which had lost only

one main stem, it underestimated the real damage by the excessive pruning. Consequently, the harvest totals for 1996/97 for open and dense shade (cf. Figure 3-10) are below the values that could have been expected given appropriate pruning. The real values for 1996/97 might have been between 25 and 30 kg of fresh fruit for the open and dense shade treatments (compared to 18 to 22 as measured), thus reducing the fluctuations in Figure 3-10 markedly.

The reduced fruit drop under shade (Figure 3-11) may have been due to the higher capacity of shaded plants to retain ripe berries on the plant (pers. obs.) and to the physical protection of ripe fruits from the impact of raindrops by the tree canopy and the higher foliation of the shaded coffee bushes. The higher amount of rejects among the harvested fruits of the sun and pollarding treatments were probably due to the higher heat loads, higher disease incidence, and reduced vigor of the plants supporting the fruits. The small percentage of deformed fruits from the shadecloth treatment may be due to the extremely high production of those plants in 1995/96. Physiological imbalances might have increased the incidence of deformed fruits (Wormer 1964a).

Although the total number of fruits (TF = "potential production") is not usually assessed in commercial farms it

is often estimated by comparing the apparent "fruit load", i.e., the number of fruits set (and before that, the "flower load") on the plants. Such subjective assessments are routinely done by coffee producers before the plants show the first symptoms of over-bearing, disease infestation, or even die-back as the fruits mature. Hence the later fruit losses (RF and FF in Equ. 3-1; Figures 3-11 and 3-12) are not taken into account. Nevertheless, these visual impressions often trigger decisions about shade and tree management, since the differences in potential production among plants exposed to different shade intensities are easy to see. As a consequence, many farmers decide to prune shade trees severely in order to prevent an expected decline of production under shade. However, as demonstrated in Figure 3-13, such a decision could be incorrect since it should not be based on perceived PP but rather on the amount of quality fruit harvested (QF, Figure 3-13C) which is, under the conditions of Turrialba, strongly benefitted by shade.

There were three lines of evidence to suggest that shade *per se*, and associated microclimatic effects, were more important for determining coffee production than nutrient contributions of the trees: (i) The nutrient additions in the pollarding plots did not increase the production of those plots over the sun plots. However,

negative effects of the large microclimatic fluctuations in the pollarding plots may have masked positive effects via nutrient inputs; (ii) the nutrient inputs via pruning residues were relatively small (< 48% of the fertilization) compared to the fertilizer inputs (Table 3-5); and (iii) at similar yearly shade averages, the shadecloth treatment produced equally high amounts of coffee as open shade even though it did not receive any additional nutrient input from trees. The smaller shade-induced yield reduction for Catimor 5175 compared to Caturra may indicate a relatively larger shade adaptation of this variety.

The observation that shade benefitted coffee production under the low-elevation, and hence suboptimal, conditions of Turrialba complements the work of Ramirez (1993). That author concluded, based on a 10-year fertilization X shade study under similar conditions as this study, that the shade and nutrient inputs from pollarded *Erythrina poeppigiana* benefitted unfertilized coffee plants greatly (yield increase by 65%) relative to sun-exposed unfertilized plants without the trees. However, when the coffee plants were fertilized, the pollarded trees did not increase production over the sun plots (a result that was found also in this study). This suggested that the trees' main effect was through nutrient cycling or organic matter contributions

rather than through microclimate improvement. The fertilization may have masked the effects of the nutrient inputs from the trees, and the shade intensity under the pollarded trees of the study by Ramirez, similarly as in this study, may have been too low to affect the microclimate positively for coffee. Both studies support the hypothesis that the facilitative effects of trees gain importance with increasing marginality of environmental conditions (Muschler 1997b; Holmgren et al. 1997; Callaway and Walker 1997).

Physiology and shade

The tendency for lower production of coffee in the pollarding treatment and the loss of plant vigor (this chapter) and coffee quality (Chapter 4) without shade can possibly be explained by the physiological adaptation of *Coffea arabica* to shade and moderate microclimate (cf. Chapter 1). With few exceptions (which can be explained by artefacts or peculiar experimental conditions), physiological studies at the leaf- or plant-level have demonstrated that the maximum rates of photosynthesis or growth of *Coffea arabica* are achieved at intermediate levels of shade, typically ranging from 30% to 50% (Nutman 1937; Huxley 1967; Kumar and Tieszen 1980; Nunes et al. 1993; Fahl et al. 1994). Since the light saturation of coffee occurs at relatively low levels, around 300 $\mu mol\ m^{-2}\ s^{-1}$ for shade-

adapted and 600 μmol m^{-2} s^{-1} for sun-adapted leaves (Kumar and Tieszen 1980; Fahl et al. 1994), full sunlight (exceeding 2000 μmol m^{-2} s^{-1}) can cause strong photoinhibition (Nunes *et al.* 1993). Although nitrogen fertilization can reduce the extent of the underlying protein damage in the photosystem II, even fertilized plants can suffer long-term damage from sudden exposure to full sun (Nunes et al. 1993). For the agronomic management, such physiological responses become particularly important where the shade stratum above the coffee is managed periodically as in the case of the pollarding treatment. As described above, this traditional management of the shade trees around Turrialba exposes the coffee to such drastic changes from shade to sun two or three times per year, and self-shading of the plants may reduce, but not eliminate, the effect of sudden exposure on the interior leaves of the plant.

The high temperatures of air, leaves and soil (Figs 3-4 to 3-6) also contribute to explain the reduced plant performance in the sun and pollarding treatments. According to Nunes et al. (1968) coffee plants exposed to air temperatures above 25°C suffer a 10% reduction of photosynthetic rate for every degree C increase. This response, if similar for the conditions and varieties studied here, would represent a significant cost for

unshaded coffee plants that were exposed to temperatures above 25°C for up to five hours in the current study (Fig. 3-4). At peak temperatures of up to 32°C around noon, net photosynthesis might approach very small values as reported by Nunes et al. (1968). Strong reductions of photosynthetic rates were also reported by Kumar and Tieszen (1980) for air temperatures exceeding 26°C. In contrast, the shaded plants in this study were exposed to optimum temperatures during the whole day, barely exceeding 25°C at noon (Fig. 3-4). The microclimatic contrast betwen sun and shade plots was also illustrated by the differences in vapor pressure deficit (Fig. 3-4) and leaf temperatures (Fig. 3-5) which, in full sun exposure, exceeded optimum levels during several hours of the day (Maestri and Barros 1977). The high soil temperatures of the sun-exposed plots were markedly above the optimum for root growth (Franco 1958).

Besides the benefits to photosynthesis of moderate temperatures under a "dappled" shade (Jones 1992), coffee photosynthesis might also benefit from the short direct sun as sunflecks pass over coffee leaves over the course of the day. During short sunflecks, post-illumination carbon-fixation can increase measured carbon gain substantially over the predicted values (Chazdon 1988). If this applied

also to coffee, it might have contributed also to the unexpectedly high production under the high shade levels.

Vegetative condition

The higher leaf loss of the plants in the sun and pollarding treatments towards the end of the harvest period was probably the result of plant exhaustion, indicated by foliar discolorations due to nutrient imbalances, and higher susceptibility to diseases (Müller 1959; Agrios 1988). During fruit filling, coffee plants are reported to have higher nitrogen requirements (Müller 1995) which probably also holds for other nutrients. If this demand is exacerbated by additional high insolation (see discussion above) the plants might not be able to provide enough nutrients to the various sinks resulting in decreased vigor, leaf loss, and, ultimately, die-back of whole branches or plants (Nutman 1937; Rodriguez 1935; Carvajal 1984; Wrigley 1988). The observation that the difference in foliation retention between the sun/pollarding plots and the open/ dense shade plots was larger for Catimor 5175 than for Caturra (Figure 3-14C), suggests a higher "robustness" of Caturra under unshaded conditions.

Deficiencies and diseases

The higher disease incidence in the open and dense shade treatments was probably linked to the extreme

microclimatic conditions there, and a higher nutrient demand of the sun-exposed coffee plants. Nutrient stress, most pronounced during such critical periods as seed filling (Müller 1995), can predispose the plants to disease attack. Considering that K plays a key role in disease resistance (Marschner 1991; Ramirez et al. 1997), it is likely that the significantly lower levels of K in the sun-exposed plants (Table 3-6), contributed towards the higher disease loads of sun-exposed plants by reducing disease resistance (Chaverri and Alvarado 1996). The increased incidence of *Cercospora* when the potassium levels of plants are low is well-documented (Agrios 1988; Ramirez et al. 1997). Sun-induced reduction of K and Ca in coffee was described also by Tanada (1946). Besides higher demand for K of sun-exposed plants, K leaching from the coffee foliage may have contributed to reduce foliar concentrations, while the plants under *Erythrina* may have been exposed to less leaf leaching and, possibly, even some K inputs from the throughfall of the *Erythrina* canopy.

The moderate microclimate under the open and dense shade treatments may have reduced the susceptibility of the plants to diseases, particularly *Cercospora* which does not develop under shade (ICAFE-MAG 1989). Studying *Coffea arabica* in its native Ethiopia, Sylvain (1955) reported also

on the strong reduction or virtual absence of diseases (*Cercospora* and *Hemileia*) on coffee plants as long as they were under shade. The disease behavior documented in this study supports the conjecture that coffee still maintains a relatively high adaptation to shade, evidenced by the benefits of shade.

Management Costs of Shade Treatments

In order to assess the full economic impact of the different shade treatments, the management costs and revenues need to be monitored in detail. Although this information is not available here, it is possible to estimate the dimension of the economic impact by contrasting selected production costs of the sun and pollarding treatments with those of the open shade treatments.

Assuming similar production levels for the treatments (a reasonable assumption as demonstrated for the sun, pollarding and open shade treatments in this chapter), and similar prices for coffee, independent of quality (for simplicity), the main economic differences among shade treatments are in the costs for tree pruning and weed management. The other costs (cf. Appendix) are probably similar among the shade treatments. While tree pollarding accounted, between 1994 and 1996, for about 2% of total production costs for coffee at "Cafetalera Lindo" (Figure 3-

16; Appendix; similar to Rojas Cubero 1996), the costs for herbicides and their application in these plots amounted to 9%. Compared to the pollarding treatment, the costs for the selective pruning of the open shade treatments was slightly higher in the first two years, but substantially lower during years three and four (based on estimates of labor requirements); after two years of selective pruning, the trees were closer to the desired crown architecture and, consequently, less pruning was required. Therefore, the average costs for tree pruning were similar for the pollarding and open shade treatments.

Considering that weed control was unnecessary under open or dense shade (Table 3-3), and that higher amounts of recycled nutrients of the larger trees (Table 3-5) may permit a certain reduction of fertilization (subject to future study), the savings in coffee production costs by using open or dense shade vs. pollarding may exceed 10% for conditions similar to the ones studied. At a total production cost of US$ 2400 per hectare (cf. Appendix), this would equal a saving of approximately US$ 240 per hectare and year. For an average production of 35 bags of 46 kg of green coffee per hectare, this would equate to saving US$ 6.9 per bag relative to the pollarding treatment.

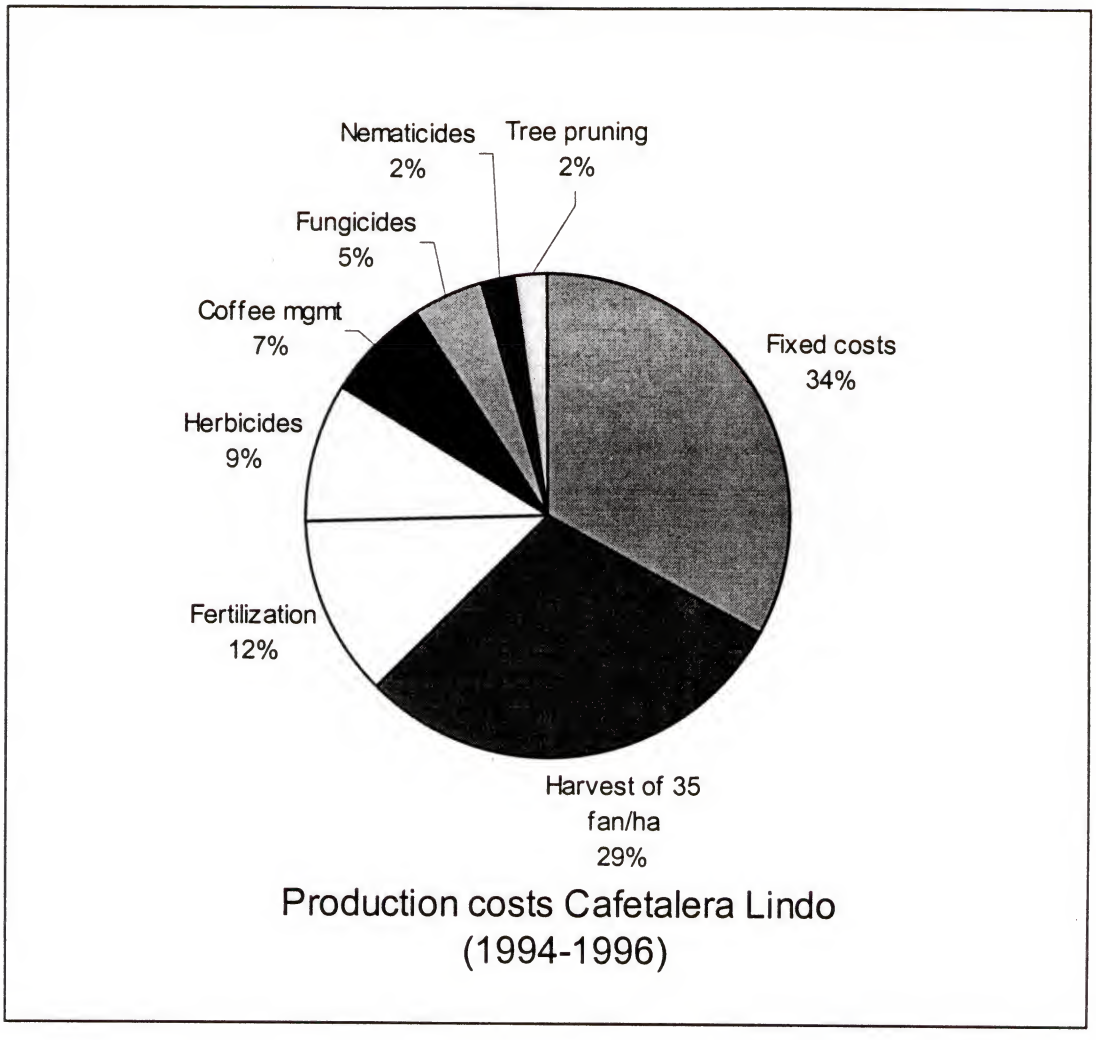


Figure 3-16. Components of total production costs for coffee at "Cafetalera Lindo" (1994 - 1996).

Compared to the sun treatment, this saving might be about 20% less (on the short term) since there is no cost for tree pruning (however, on the long term, costs for renovating a more short-lived coffee field under sun are higher). These estimates, although extremely simplified, may illustrate the potential economic benefits from maintaining

permanent intermediate shade (see Chapter 6 for recommendations on how to achieve such shading).

Furthermore, since the most common weed control in Costa Rica is via herbicides (Alvarado and Rojas 1992), chemical toxicities such as those demonstrated for Roundup® in coffee (Bouharmont and Aweno 1993) may represent additional costs of sun-grown coffee. The following chapter presents the effects of the different shading treatments on coffee quality.

CHAPTER 4
COFFEE QUALITY UNDER *ERYTHRINA POEPPIGIANA*

Introduction

The discussion of the sun-shade issue for coffee is as old as coffee production itself (Leon and Fournier 1962; Muschler 1997b; Beer et al. 1998). In the Atlantic zone of Costa Rica, most coffee (*Coffea arabica* L.) plantations include the leguminous tree species *Erythrina poeppigiana* to provide mulch and shade. Typically, these trees are pruned or pollarded two to three times per year in order to, according to the farmers, stimulate flowering and maturing of the fruit. Depending on the pruning intensity, the shade pattern can vary widely from light and dispersed shade to heavy and homogeneous shade (Beer et al. 1998). Despite the many discussions on the best levels of shade (e.g., Fournier 1988; Muschler 1997a and b; Beer et al. 1998; Fernandez and Muschler 1998), there is relatively little information on the effects of quantified shade in different environments. In particular, there is sparse information on coffee quality as a function of shade (Aldazábal and Alarcón 1994b; Guyot et al. 1996) although

the effects of other environmental factors on the development of coffee berries have been discussed by various authors (Wormer 1964a and b; Cannell 1974).

This chapter summarizes the effects of different shade regimes provided by *Erythrina poeppigiana* on the quality of *Coffea arabica* var. Caturra and Catimor 5175. The quality assessments were based on size and deformations of the fruits/beans as well as on a blind tasting experiment. This information complements the data of shade effects on coffee production of the preceeding chapter.

Materials and Methods

Research Site

The data for this study were collected on plots in a commercial coffee plantation of "Cafetalera Lindo S.A." in Turrialba, Costa Rica (9°55'N, 83°41'W, 700 m.a.s.l., slope < 5%, 21°C, 2600 mm, no marked dry season). The soil was classified as Typic Hapludand with a pH_{H2O} in the topsoils of 5.0 to 5.5 and medium levels of nutrients except for low levels of P and K (for details see Chapter 2).

Coffee Management

The plants of *Coffea arabica* var. Caturra and Catimor 5175 (5000 plants ha^{-1}) were between six and ten years old

and the shade trees of *Erythrina poeppigiana* between 15 and 20. Coffee management was intensive with two fertilizations of each 315 kg ha^{-1} a^{-1} of "complete" fertilizer (18-5-15-6-2; N-P-K-Mg-B) and 315 kg ha^{-1} a^{-1} of ammonium nitrate (33.5% N). Weeds and diseases were controlled with herbicides and fungicides (for details see Chapter 3). All plots were managed identically except for not applying herbicides in those plots where shade suppressed weed growth.

Treatments and Experimental Design

In October 1993, five shade treatments (cf. Chapter 3) were imposed on an area that was homogeneous in terms of soil attributes and topography, as well as in population, distribution and physiognomy of coffee plants and trees. The sun, pollard, open, and dense shade treatments were replicated in four blocks (two for Caturra and two for Catimor) of a RCBD. The shadecloth plot was not replicated. The sides of each plot (including border areas) measured between 30 m and 40 m. The sides of the net plots, which consisted of 25 plants each, measured 10 m to 15 m.

The shade treatments covered a range of shading from 0% in the sun treatment to a yearly average of 86% in the dense shade treatment. The shadecloth projected a homogeneous shade in space and time of 55 to 60%. The

pollarding and, to a lesser extent, the open shade treatments exposed the coffee to microclimatic changes at the times of pruning or pollarding.

The shading was measured once per month as PAR interception relative to the unshaded plots, using a Sunfleck Ceptometer (Decagon Devices Inc.) on transects through the plots. Detailed information on shading and microclimatic patterns, as well as on coffee plant vigor and production in the different treatments is described in Chapter 3.

Parameters, Sampling and Sample Processing

Fruit weight was measured as the fresh weight (g) of 100 randomly selected ripe fruits (W_{100}) from each plot taken on 10 sampling dates (roughly at two-week intervals, spanning the whole harvest period) for the harvest 1994/95 and on 3 sampling dates in 1995/96.

The data for bean size distribution (all treatments; four samples per treatment; harvest 1995/96) and the organoleptic (taste and smell of the brewed coffee) studies (unshaded and dense shade treatments only; three composite samples per treatment for Catimor 5175 and one for Caturra; harvest 1997/98) were based on composite samples of two kg fresh weight each. Each composite sample consisted of five subsamples per plot taken randomly from different batches

of coffee harvested in each plot at the time of the harvest peak. This made it necessary to sample the shaded plots between three to four weeks after the unshaded plots. Only fully ripe fruits were included in the samples.

The coffee fruits ("beans") were processed in the experimental "beneficio" of CATIE following the standard "wet process" (Wrigley 1988) of depulping the beans within 24 hours of harvest, followed by soaking and fermenting the samples for 24 to 36 hours and a final washing to remove the mucilage from the beans. Then the samples were oven-dried at 40 to 50° C until reaching 10% to 12% humidity. After hand-removal of the parchment (endocarp) to avoid breakage, the beans were passed through a series of sieves with round perforations of 17, 16 and 15 sixtyforths of an inch in diameter (6.7 mm, 6.4 mm and 6.0 mm, respectively). The weight fractions retained on each sieve were recorded and converted to weight percentages of the total sample.

Visual appearance and organoleptic attributes were evaluated by the professional coffee taster Gerardo Astua at the tasting laboratory of the Costarican "Centro de Investigaciones en Café" (CICAFE). First the parchment-free green bean samples were visually classified in five quality categories, from 1st grade export quality to 5th grade coffee for local consumption. These classes were subsequently

transformed to correspond to a scale of 1 (worst) to 10 (best). Low-grade coffee is characterized by heterogeneity of size, symmetry and color of the beans, curved or irregular center cuts, and a high ocurrence of deformations, such as pea beans ("pea berries"; only one of the two beans develops in the fruit) or triangular beans (three beans per fruit; Menchú 1966; Wormer and Njuguna 1966; Wrigley 1988).

The tasting protocol followed the standard CICAFE procedures. For each sample, 200 g of green coffee beans were roasted to a uniform light brown color. This standard procedure allows best to detect off-flavors and defects (G. Astua, pers. comm., 1997). For visual appearance of the roasted beans, homogeneity of roasting, physical shape, and defects of the roasted beans were valued on a scale of 0 to a maximum of 10 for well-formed beans of homogeneous size and color that were free of physical deformations or discoloration. For tasting, two subsamples of 11 g each were ground from each sample and used to brew two cups of coffee for each sample. The liquor quality of coffee was assessed as aroma by smelling the freshly brewed cup, and as body (syn. mouthfeel or viscosity *sensu* Clifford (1985)), acidity and cleanness of the coffee in the mouth. Under cleanness of taste, off-flavors were described.

Aroma, body and acidity were given values on a scale of 0 (worst) to 10 (best quality).

Statistical Analysis

Means were compared with standard procedures of ANOVA and t-tests. Multiple mean comparisons followed Duncan's Multiple Range Test and orthogonal contrasts for group comparisons. Bean size distributions were compared with contingency tables based on Chi-square tests. Differences were declared significant for $\alpha \leq 0.05$.

Results

Fruit Weight

The evaluation of fresh fruit weights (W_{100}) separated the treatments into two groups: the two treatments with tall homogeneous shade of *E. poeppigiana*, "open shade" and "dense shade" yielded significantly heavier fruits (by 11 to 14 % relative to sun) than the treatments "sun" and "pollard" (Figure 4-1). This difference was consistent for all harvest events. The unreplicated shade-cloth treatment was not included in the ANOVA. Nevertheless, as expected, its homogeneous intermediate shade yielded an intermediate W_{100} demonstrating the effect of shade *per se*, i.e. without being confounded with other effects generated by the trees

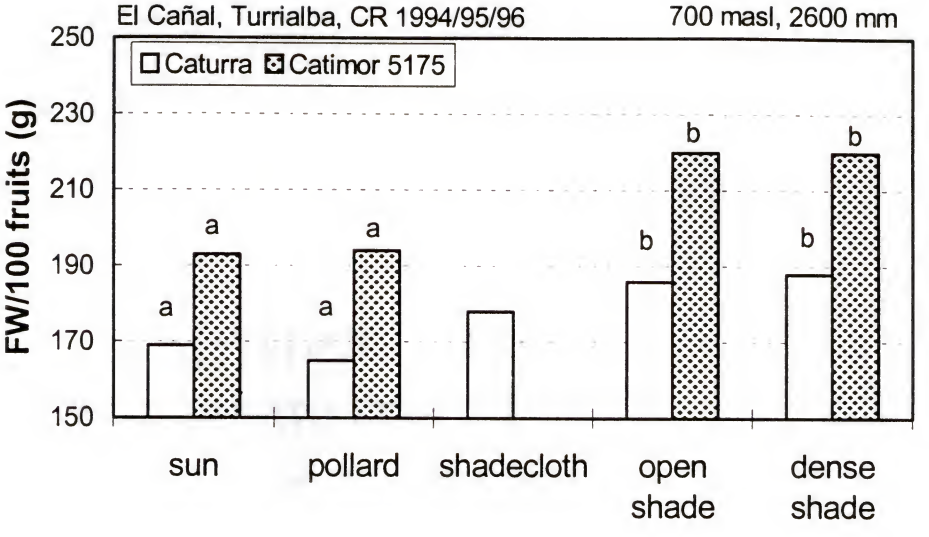


Figure 4-1. Fresh weight of 100 ripe fruits of two coffee varieties grown under increasing shade levels (from left to right). Within varieties, means with the same letter did not differ significantly (n=26, α=0.05). The varieties were significantly different.

but not by the shadecloth (e.g., organic matter/nutrient cycling). The increase in W_{100} under open and dense shade was similar for both coffee varieties (Figure 4-1). The values for Catimor were consistently higher by 17% compared to Caturra when averaged across all treatments.

Fruit-to-Bean Conversion Factors

The ratios between fruit fresh-weight (FW_{fruit}) and the corresponding dry-weight of parchment coffee (DW_{parch} = dried depulped beans with the silverskin and endocarp/parchment) and dry-weight green coffee (DW_{green} = dried depulped beans without parchment; this is the coffee for export) did not reveal any significant differences between varieties (data not shown) or treatments (Table 4-1), although there seemed to be a slight tendency towards lower conversion rates for the sun treatment. The ranges of the individual plot data were 15-19% for DW_{parch}/FW_{fruit}, 12-16% for DW_{green}/FW_{fruit} and 80-85 for DW_{green}/DW_{parch}.

Bean Size

The size distribution of green beans ("café oro") showed a significant and consistent increase in bean size with increasing shade levels for both coffee varieties (Figure 4-2)(X^2-tests: $P < 0.1$ for Caturra and $P < 0.01$ for

Table 4-1. Conversion factors from fresh weight of fruits (FW_{fruit}) to dry weight of beans with parchment (DW_{parch}) and to green beans for export (DW_{green}), as well as DW_{parch} to DW_{green}, for the shade treatments in El Cañal, Turrialba, Costa Rica (700 m a.s.l., 2600 mm per year). Values for Caturra and Catimor were pooled since they did not differ. The treatments did not differ statistically ($\alpha = 0.05$).

Treatment[@]	DW_{parch}/FW_{fruit} (%)	DW_{green}/FW_{fruit} (%)	DW_{green}/DW_{parch} (%)
T1 (sun)	16.9	13.7	81.4
T2 (pollard)	18.0	14.7	81.8
T3 (open shade)	18.2	15.0	82.7
T4 (dense shade)	17.8	14.7	82.4
T5 (shadecloth)	18.1	15.1	83.4

[@] n = 4, except for T5 where n = 1; therefore T5 was not included in the statistical comparison.

Catimor). The proportions of large beans (diameter > 17/64 inch or 6.7 mm) in the open and dense shade treatments were significantly higher than in the sun treatments. The comparison between the shadecloth and pollarding treatments for Caturra indicated higher proportions of large beans and small beans (diameter < 15/64 inch or 6.0 mm) for the pollarding treatment (Figure 4-2). This result was unexpected because shading was more intense under the shadecloth than in the pollarded plots. The described patterns held for both varieties (Figure 4-2). However, contrasting the bean size distributions of "sun" and "dense shade" for the two varieties indicated a larger benefit of shading for Catimor 5175. While the increase in percent large beans from sun to dense shade was 20% (from 49% to 69%) for Caturra, it was 29% (from 43% to 72%) for Catimor 5175 (Figure 4-2). Similarly, the reduction of small beans was larger for Catimor 5175 with 14% (from 18% to 4%) *vs.* 9% (from 14% to 5%) for Caturra.

Visual Appearance and Organoleptic Attributes

With the exception of aroma, both varieties benefitted consistently from shade (Figure 4-3). For Catimor, shade improved the appearance of green ($P < 0.01$) and roasted ($P < 0.1$) beans. Shade also improved both taste parameters

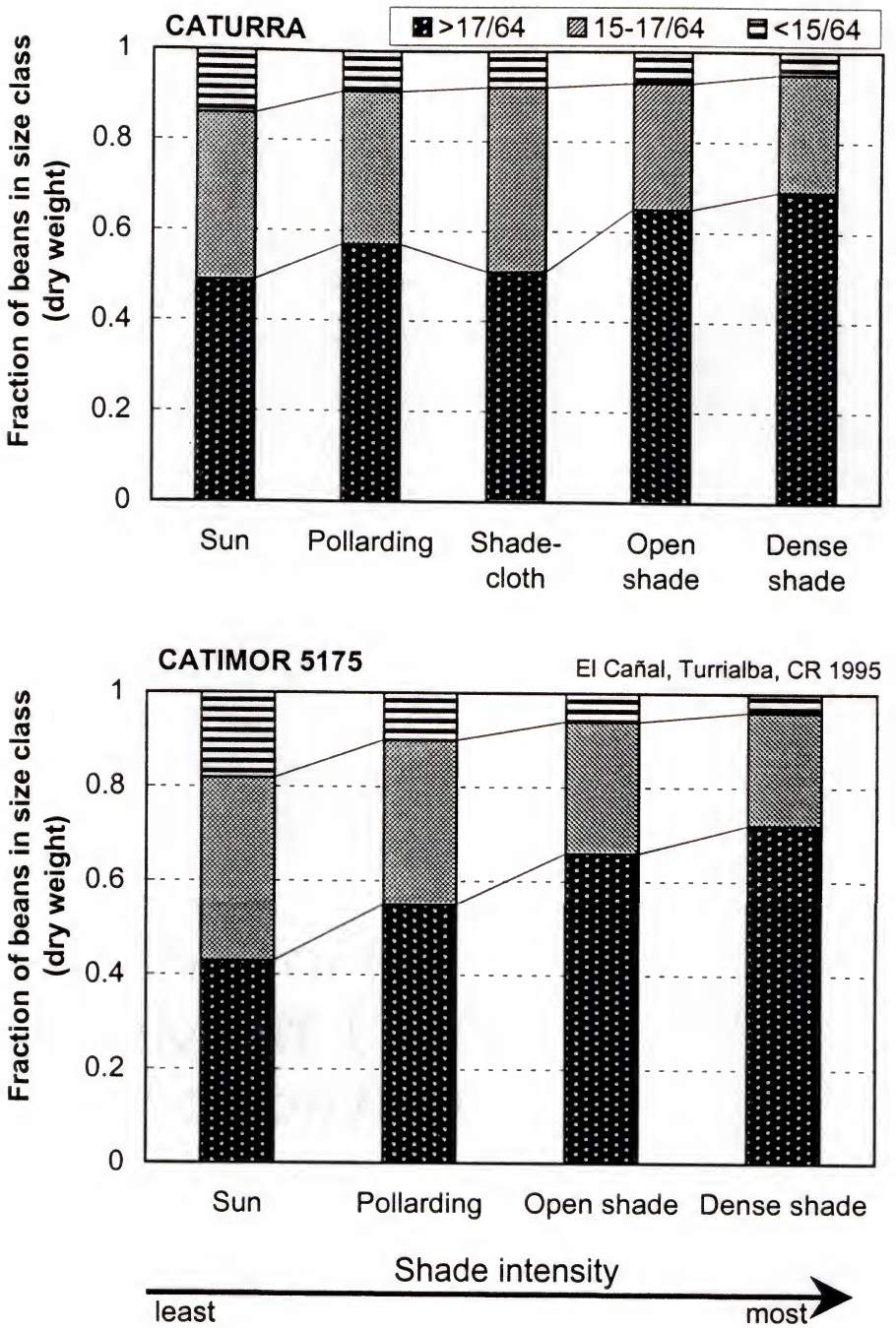
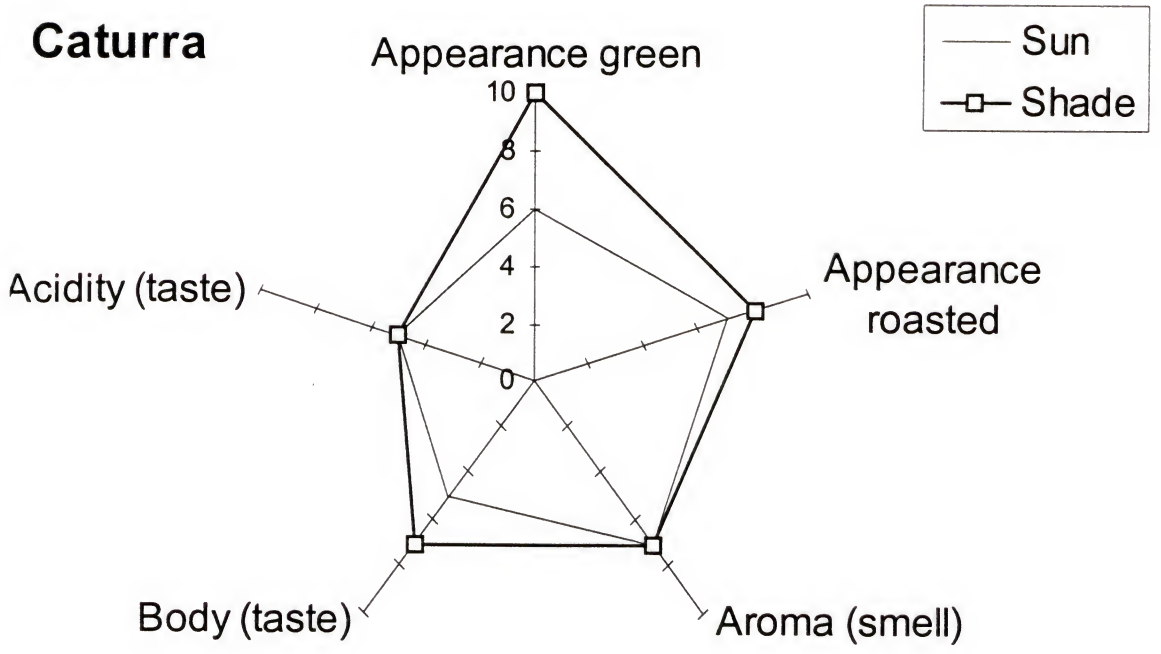


Figure 4-2. Size distribution of green beans of *Coffea arabica* var. Caturra (above) and Catimor 5175 (below) under increasing shading (left to right) in a low-elevation coffee area of Costa Rica (700 m a.s.l., 2600 mm rain per year). Units of bean diameters are inch.



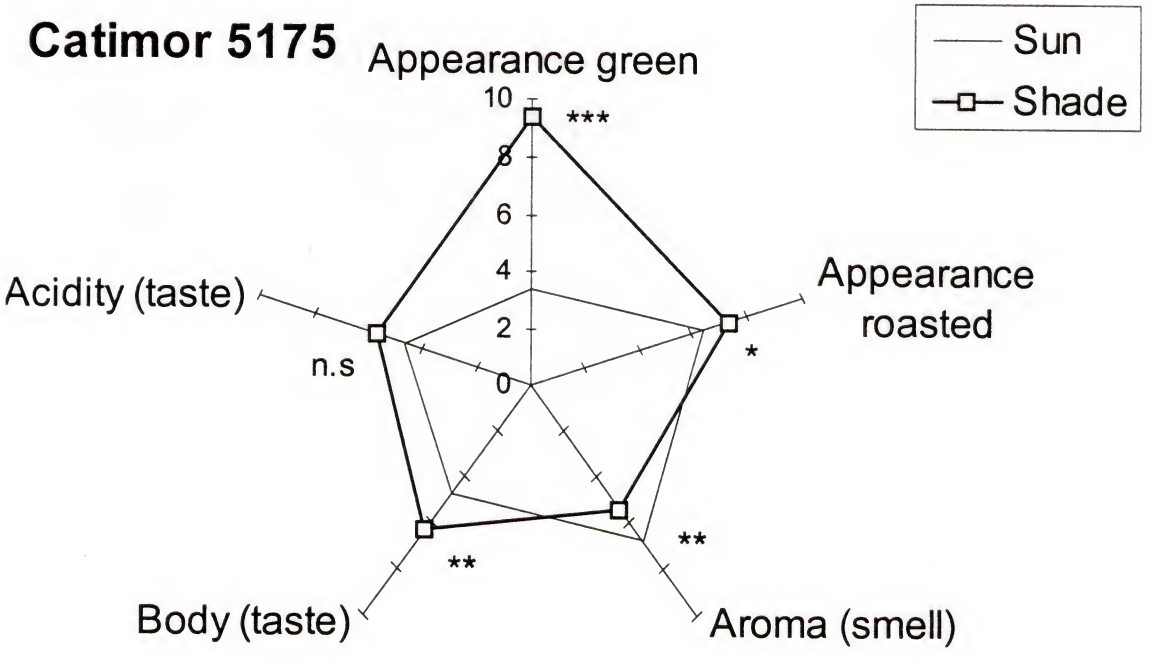


Figure 4-3. Quality attributes of green and roasted beans of two varieties of *Coffea arabica* grown in full sun and with intermediate shade (< 50% PAR) of *Erythrina poeppigiana* at a low-elevation site in Costa Rica (El Cañal, Turrialba, 700 masl, 2600 mm). Beans were harvested at full maturity in Sept/Oct 1997. The scales use a relative index with a maximum of 10. Significance between sun and shade given as ***α=0.01, **α=0.05 and *α=0.1.

(body and acidity) although only the difference for body was significant. In contrast, the index of aroma was significantly lower for shaded Catimor (Figure 4-3). For Caturra, a similar pattern was found for all parameters, except for aroma and acidity, with the differences between treatments being slightly smaller. Again, the observation of larger differences for Catimor 5175 than for Caturra may indicate the higher shade requirements or tolerance of Catimor 5175.

Among the other parameters described, two of the three sun samples of Catimor had an undesirable medicinal off-flavor that was not detected in any other sample. Sun-samples also were the ones with higher incidences of deformed beans such as pea berries. This information, however, was not quantified separately since it was reflected already in the index of green bean appearance.

Discussion

Fruit Weight

Production of the larger and heavier fruits with increasing shade coincides with results of other authors who documented a beneficial effect of shading, primarily through temperature reduction and an extension of the time for maturing (Cannell 1974; Aldazábal and Alarcón 1994b; Guyot

et al. 1996). Although the shadecloth treatment was not replicated, and therefore was not included in statistical analyses, it is interesting to note that it produced berries of intermediate weight. This result corresponds well with the shading intensity of the shadecloth which was also intermediate between the sun and pollarding treatments on the one side and the open and dense shade treatments on the other. Since the shadecloth treatment excluded other potentially important secondary effects of trees (e.g., via nutrient cycling or root interactions/turnover), it appears that the observed differences in W_{100} were predominantly due to the differences in shading and not to other factors. This result is indeed likely since both abundant nutrient and water supply in the experiment may have limited the importance of tree-coffee competition for these resources. However, by the same token, these conditions may also limit the applicability of these result to other areas.

Fruit-to-Bean Conversion Factors

The absence of significant differences in conversion ratios between the two varieties and among treatments permits using fresh fruit weights for comparing different shade treatments. Especially the W_{100} for fresh ripe berries, a quickly and easily measured quantity, appears as a promising and simple indicator of bean size. Relative

constancy of conversion ratios also permits easy calculation of dry-weight green bean equivalents which are more tedious to measure on a routine basis. However, given that the conversion factors of fresh fruits to parchment beans and to green coffee were more than 1 % higher (although statistically not significant) in the shade treatments compared to sun (Table 4-1), the independence of conversion factors from shade levels needs further scrutiny before adopting this procedure. Higher fruit to green coffee conversion factors in shade (17.3%) relative to sun (16.7%) were also reported by Hernandez (1995). If confirmed, such differences would present an additional benefit of shade and would have to be considered for interpreting the fruit weight as an indicator of bean weight.

Bean Size

The increase of bean sizes with shading agrees with studies from other coffee areas (Abruña et al. 1966; Aldazábal and Alarcón 1994a and 1994b; Guyot et al. 1996). However, the relatively stronger representation of the size extremes in the pollarding treatment compared to the shadecloth was surprising since the average level of shading in the pollarding treatment was lower than that of the shadecloth. If bean size increased steadily with shade,

the opposite would have been expected. One hypothesis to explain this result deals with the patchiness of shading in the pollarding treatment which contrasts strongly with the homogeneous shading, both in time and space, under the shadecloth. The patchy shading in the pollarding treatment causes those coffee bushes closest to *Erythrina* trees to be exposed to relatively high levels of shading during some parts of the year. It could be berries from these plants that contribute to the higher proportion of the large beans under pollarding. At the same time, however, there are a number of plants that are little influenced by any tree, and it might be these (sun-exposed) plants that produce small beans - similar to the sun treatment. These two groups of coffee bushes, exposed to contrasting extreme conditions despite being in the same treatment, might account for the relatively larger proportions of large and small beans. In contrast to this patchy shade, the homogeneous shading under the shadecloth eliminates such differences in individual-plant shading. This artificial shading may be strong enough to reduce the proportion of small berries relative to the sun treatment (Figure 4-2) but is possibly not intense enough to significantly improve the conditions for the development of large berries.

The relatively larger benefits of shade on bean size of Catimor 5175 (29% increase of large beans vs. 20% for Caturra; Figure 4-2) could indicate a possibly higher shade tolerance of Catimor 5175 compared to Caturra. This concurs with the slightly smaller yield reduction of only 12% under dense shade vs. no shade for Catimor 5175 compared to Caturra where dense shade reduced production by 37% (Figure 3-9, Chapter 3) and with observations of local coffee experts. However, the validity of this interpretation needs to be tested in the future.

Visual Appearance and Organoleptic Attributes

Since taste and visual appearance of coffee, the characteristics that were improved by shade, are more important for the overall judgement of coffee quality than aroma (smell) of the brew (G Astua, pers. comm. 1997), it was concluded that organoleptic coffee quality was greatly improved by shade. The improvements were greater for Catimor 5175 than for Caturra mainly due to the lower ratings for the sun-grown Catimor 5175 compared to Caturra (Figure 4-3). Relatively low quality ratings of sun-grown Catimor 5175, compared to other varieties, were also reported by Astúa and Aguilar (1997). However, it is interesting that the organoleptic quality of shaded Catimor was almost the same as that of shaded Caturra (Figure 4-3).

Shade-induced improved quality of organoleptic properties was also reported by Guyot et al. (1996) for *Coffea arabica* var. Catuai from high-elevation zones in Guatemala. In that study, shading also increased the acidity and the sucrose content of Catuai, both important ingredients of organoleptic evaluations. The primary reason for that positive effect was reported to be the delayed ripening due to the shade and its microclimatic effects. It is likely that the same factors contributed to the higher quality in the present study. In addition, it is probable that the reduction of temperature extremes in this low-elevation coffee zone through shading (cf. Chapter 3; Barradas and Fanjul 1986; Jaramillo-Robledo and Gómez-Gómez 1989) played a major role in the uniform growth and ripening of berries under shade. This might also have been the main reason for improved coffee quality under environmental conditions outside of the optimum biophysical range for coffee. The improved coffee quality with increasing elevation and, hence, reduced temperatures reported from Guatemala (Figueroa 1997) supports this contention.

In contrast to Guyot et al. (1996), Barboza (1991) found only inconsistent differences in coffee quality between sun-exposed and shaded plots. However, this

was probably due to the low levels of shading studied that were similar to the pollarding treatment of the present study. As shown also in the present study, the shade pattern of the pollarding treatment (Figure 3-3) was too patchy to significantly and consistently improve coffee quality over that from the sun plots (Figures 4-1 and 4-2).

Conclusions and Recommendations

The data presented showed a substantial improvement of coffee quality through shading in a suboptimal and high-temperature environment where coffee plants are stressed. The main benefits from shading were (1) higher weights of fresh fruits, (2) larger beans, (3) higher ratings for visual appearance of green and roasted beans, (4) higher ratings for acidity (Catimor 5175 only) and body, and (5) absence of off-flavors. The only parameter that was decreased for one of the two coffee varieties under shade was aroma. However, coffee tasters consider this parameter as less crucial than the others. Future economic analyses of the different coffee management options should take these differences into account.

The comparison between varieties suggests that Catimor 5175 responded more favorably to shade than Caturra which might indicate a higher shade adaptation or requirement for

Catimor 5175. However, such varietal differences in shade adaptation, and hence potential "agroforestry compatibility," will have to be substantiated by further studies specifically designed for this purpose.

The suboptimal environmental conditions of this study are typical of many low-elevation coffee areas and the stress to which sun-grown coffee plants are exposed can be expected to be further aggravated by fertility and moisture limitations. Under such conditions, it is possible that the shade benefits shown in this study might be even greater. The obligate use of shade in the dry coffee zones on the Pacific side of Central America (e.g., Guanacaste in Costa Rica, Nicaragua, San Salvador)(Rodriguez 1935) lends credence to this conjecture. On the other hand, in more favorable coffee zones with only slight or no edaphic or climatic limitations, these differences might disappear or even be reversed if shading or other tree effects were to become a stress factor to coffee. Considering the growing importance of product quality for the emerging specialty markets such as gourmet coffee or organic coffee, studying the effects of shading on coffee quality deserves more emphasis. In particular it is important to investigate the interaction between shade effects and biophysical environment for coffee to generate meaningful

recommendations for the ecologically diverse coffee regions of Central America.

CHAPTER 5
COFFEE UNDER CONTRASTING TREE SPECIES

Introduction

Farmers have three main tools to manage the effects of trees in an agroforestry system: tree spacing and spatial distribution, pruning, and species selection. With the first tool, tree spacing and distribution, they can predetermine or guide the intensity of the tree-crop interactions (Jackson and Palmer 1972; Cain 1972; Jackson 1985). This operates over long time periods. Spacing is only changed by tree mortality, usually most pronounced in the first years after planting, or by thinning/selective harvesting, usually at five to ten-year intervals. Orientation of tree rows, as a function of latitude can be a powerful tool for managing light penetration (Cain 1972; Jackson and Palmer 1972; Jackson 1985).

The second tool, tree pruning, permits fine-tuning the tree-crop interaction. Pruning can be used on demand at any time. The intensity and frequency of pruning modifies the degree of microclimatic modification by the trees (Cain 1973; Monteith et al. 1991), and indirectly affects

belowground interactions via pruning-induced die-back of roots and symbionts (Cannell 1983; Nygren 1995). At the same time, pruning affects productivity and carbon allocation patterns of trees (Russo and Budowski 1986; Nygren 1995). The choice, use, and effectiveness of these latter two tools depend to a large extent on the environmental conditions at a specific site and on the tree species used (Huxley 1983b).

The selection of appropriate species for a given environment and production objectives is the third main tool of farmers (Jackson 1989; Huxley *et al.* 1989; Wood 1990; Nair 1993; Haggar and Ewel 1997). Species attributes such as growth rates, crown architecture, foliar distribution, phenological patterns, root distribution, and resource use efficiencies determine the intensity of potential interactions with coffee (Cannell 1983; Huxley 1983a, 1983b; Kuuluvainen and Pukkala 1987; Beer 1987a; Jackson 1989; Callaway 1995; Casper and Jackson 1997; Beer et al. 1998). These attributes, in turn, determine the appropriate tree spacing and pruning regimes and strongly affects the management of weeds (Staver 1995), diseases, and pests (Proyecto CATIE/MAG-MIP 1995). Taken together, these factors demonstrate the power of tree species selection for the development and management of coffee systems. However, the utility of this tool depends on the amount of information

available about these tree-crop interactions, which is still very superficial (Beer et al. 1998). The relative dearth of information on phenology and other attributes of tropical tree species candidates (e.g., Frankie et al. 1974; Newstrom et al. 1994) handicaps tree species selection based on their anticipated eccological behavior (Huxley *et al*. 1989).

Unfortunately, financial and time constraints limit the option to plant species candidates (for Central America probably hundreds of species) in an experimental design into coffee plantations and to monitor the tree-crop interactions over long periods of time. In many cases, the evaluation of tree-coffee interactions can require on the order of five years to several decades (Huxley 1990; Beer et al. 1998). This work would be further complicated by the need to study these interactions as a function of coffee varieties, and along gradients of biophysical environments and management regimes. And finally, this "plantation approach" would most likely also suffer from the inevitable differences between the researcher-guided management and the farmers' management. The latter is often more dynamic in response to shifting priorities or conditions, and closeness to farmers' realities and decision behavior is a key for the probability of technology adoption by farmers (Pretty 1995; Hildebrand and Russell 1996).

Consequently, other avenues for collecting information about tree-crop interactions need to be developed. In particular, the methodology should permit use of trees already established in coffee fields to evaluate their effects on coffee rapidly and at low cost.

This could be achieved through a "transect-based" evaluation of coffee performance to characterize the overall shade tree effects on coffee as a function of distance between individual coffee bushes and the tree trunk. I studied the feasibility of this approach for individual trees of five tree species. The specific objectives were to:

1. Determine whether the distance between coffee plants and individual trees affects coffee performance.

2. Compare individual trees of contrasting tree species with respect to their compatibility with coffee.

The Transect Approach

The effect of trees on coffee that is most important to farmers is on yield and vegetative condition of the coffee plants. The positive effect of a given tree species, say a compatible species, on coffee would increase these parameters over those from a field without trees or with noncompatible trees. Assuming that the overall effect of the population of trees in a coffee plantation is the sum of the

effects of each individual tree,[1] then each tree contributes its share to the overall effect. For each tree this would define an "area of influence" (AI), where the tree affects the performance of the coffee plants growing within it (Figure 5-1A). Coffee plants outside this area would not be affected by the tree and, hence, would differ from the plants inside. Consequently, the differences between coffee plants within and outside the AI, positive or negative, and their magnitude would indicate the overall effect of the tree species given. The simplest approach to describe these differences would be to sample groups of coffee bushes within and outside the crown area or AI of the tree species of interest, using individual trees as replicates. However, depending on the balance between above- and belowground interactions (Wilson 1988), the AI may or may not coincide with the crown area of the tree. Consequently, without prior knowledge about the limits of the AI (the situation for most tree species), it would be difficult to define which coffee plants are in fact influenced by the tree and which are not.

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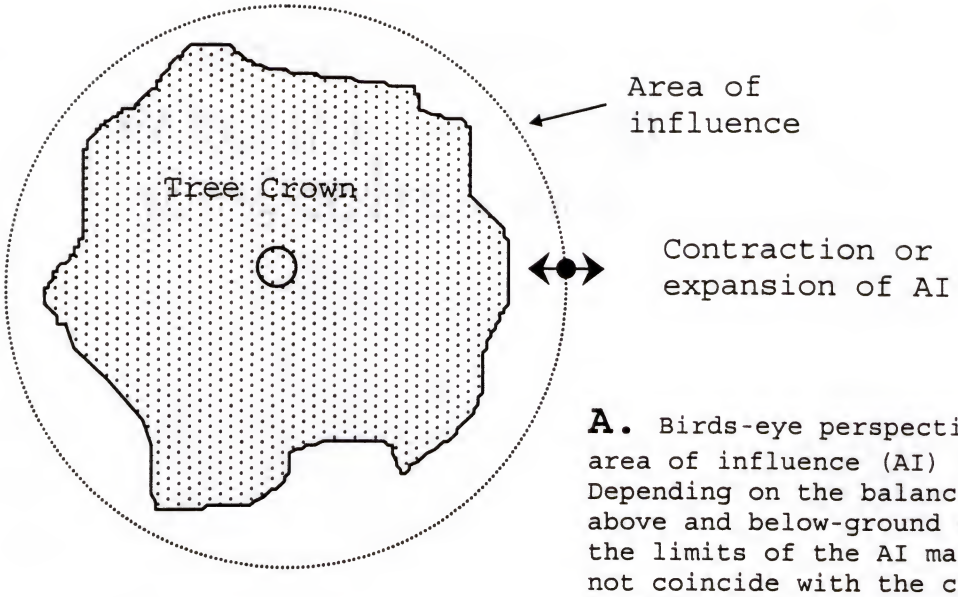
[1] Although synergistic and non-linear interactions (Odum 1983) may render this assumption of additivity invalid for closely spaced multi-species systems, it may hold for widely spaced trees such as the ones used for this transect approach.

Since the effects of a tree are likely to change continuously, rather than discretely, with increasing distance from the tree stem, an alternative way to evaluate these effects could be by regressing some parameter of coffee performance, such as yield, vigor or foliation, on the distance from the tree stem (Figure 5-1B). Positive or neutral slopes of the resulting regression lines or trendlines would suggest higher compatibility with the crop than negative slopes. A similar approach was used by Tryon et al. (1992) to study how far canopy gaps could affect the growth of tree seedlings in the understory of sugar maple.

For this study, I defined a transect as the procedure of sampling coffee bushes at increasing distances from the tree stem. Compatible tree species were defined as those that improve vigor and production of coffee plants in the AI of the trees (species C in Figure 5-1). In contrast, noncompatible species reduce coffee production and vigor (species A in Figure 5-1), while a neutral species does not show any marked effect (species B in Figure 5-1). The basic assumptions for this interpretation are that the effects of the trees are (i) radially symmetrical and (ii) diminish with increasing distance from the tree. This is likely true for most species considering that shade and microclimatic modification is typically strongest closest to the tree.



A. Birds-eye perspective of the area of influence (AI) of a tree. Depending on the balance between above and below-ground effects, the limits of the AI may or may not coincide with the crown edge (see arrow of contraction or expansion of AI).

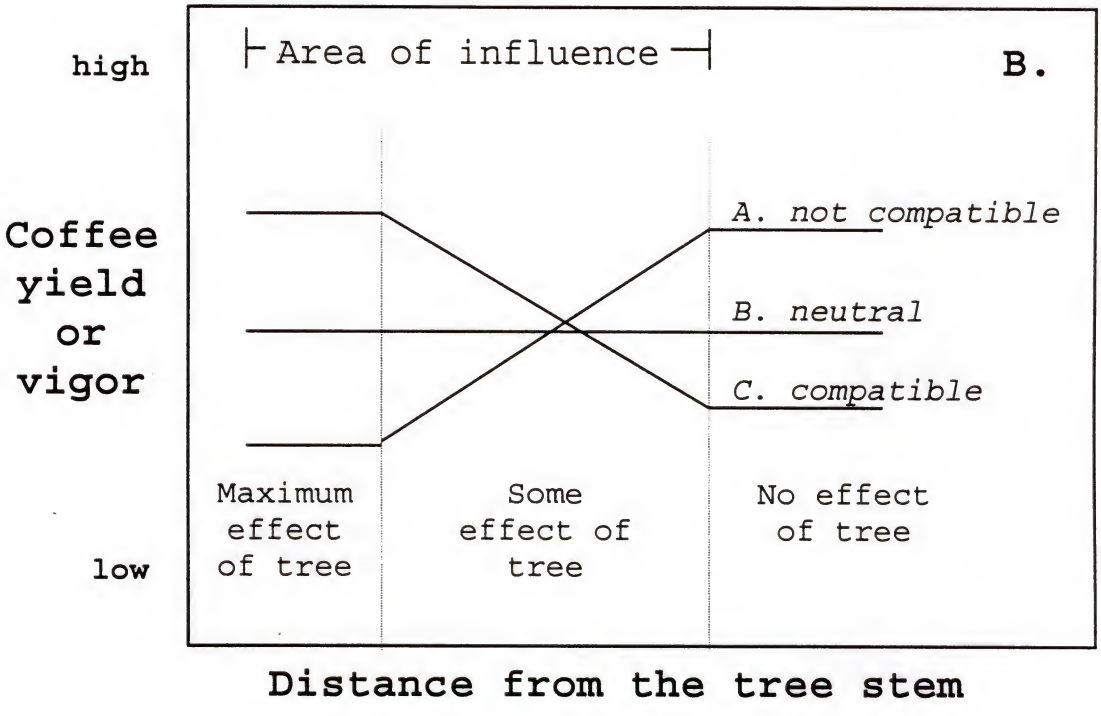


Figure 5-1. The area of influence of a tree (upper panel), and coffee performance as an indicator of the compatibility of three hypothetical tree species A, B and C (lower panel).

However, these assumptions may or may not hold for below-ground interactions where root distribution can markedly deviate from symmetrical and the highest intensity of root interactions may in some cases even be outside the crown area of the tree (Brisson and Reynolds 1994; Casper and Jackson 1997). For the purposes of this exploratory study, however, such special cases were not considered; they deserve attention in future research.

Species Selection

Due to the exploratory character and time constraints of this pilot study, only a small number of tree species could be selected. Except for *Croton killipianus*, all species were represented only by single individuals. Therefore, the information derived from the transects in this chapter applies only to the individual trees studied, and no generalizations about the species as a whole can be made from these data. Whether individual trees selected, and their effects on coffee, are representative of the species as such must be tested by replicating these individual tree transects within each environment, and be comparing the tree effects on coffee across different biophysical environments.

Care was taken to select species with contrasting crown architecture and densities, which would most likely reveal

differences in their effects on coffee. A highly compatible tree species would be one that intercepts little radiation, does not compete for water and nutrients, and that produces a high-value product in short time. The species chosen, in the order of increasing crown density (visual assessment) were: *Casuarina equisetifolia*, *Eucalyptus deglupta*, *Cassia grandis*, *Croton killipianus* and *Citrus aurantium*, all of which are found in association with coffee in Costa Rica (Espinoza 1985; Martinez 1989; Beer et al. 1998). Each species represents a group of species with similar above-ground characteristics. *Casuarina* is used as a permeable and visually open windbreak around coffee fields in the Central Valley. *Eucalyptus deglupta*, owing to its open crown and fast growth, is widely planted along field borders and as shade trees in low- and mid-elevation coffee systems. These two species have relatively open crowns causing only light to moderate microclimatic modifications. *Cassia grandis* with its tall and wide crown is one of the traditional shade tree species for coffee, representing also other species with "umbrella-shaped" crowns. *Croton killipianus* with its dense and cylindrical crown is used as a dense high-elevation windbreak, and *Citrus* is a traditional fruit tree associate found especially in smallscale coffee systems (Espinoza 1985). Of the latter three species with relatively dense

crowns, only *Cassia grandis* is deciduous during the dry season.

Methods

Research Sites

The study sites with *Citrus aurantium*, *Croton killipianus*, *Eucalyptus deglupta* and *Eucalyptus saligna* were located in coffee plantations of "Cafetalera Lindo S.A." (9°55'N, 83°41'W, 650-900 m a.s.l.), "Cafetalera Aquiares S.A." (9°57'N, 83°44'W, 700-1400 m a.s.l.), "Juan Viñas S.A." (9°55'N, 83°41'W, 700-900 m a.s.l.) and in Cervantes (9°55'N, 83°47'W, 950 m a.s.l.). All these were on the Caribbean slope of Costa Rica within 20 km from Turrialba (Fig 2-1).

The data on coffee under *Casuarina equisetifolia* and *Cassia grandis* were collected in a plantation of "Quintas Montealegre" in the Central Valley of Costa Rica, referred to as the "San José site" (9°59'N, 84°13'W, 1000 m a.s.l.; Typic Haplustand). This location, one of the few remnants with *Cassia grandis* over coffee, was about 3 km WNW of the "Instituto Nacional de Aprendizaje (INA)" on the southern side of the highway leading to the Juan Santamaría airport.

The elevation of the sites ranged from 700 to 1400 m.a.s.l.. Most sites were on flat or slightly inclined terrain with a slope of less than 5 % unless noted otherwise. More details on site description can be found in chapter 2.

Sampling Design and Plot Establishment

For each tree species, solitary trees were chosen in homogeneous coffee populations that fulfilled certain criteria (Table 5-1). As a first approximation of required sample size, I visualized a transect as consisting of two groups of plants: plants in the AI and plants outside the AI of the tree chosen. Following the calculations of chapter 2, each of these groups would have to consist of a minimum of 17 plants. Rounding the number to 20 plants per group, the minimum size for both groups would be 40. Therefore, for each transect, 40 similar-aged coffee plants (except for *Casuarina equisetifolia* for which only 20 plants were available) were chosen randomly around the tree to be studied. The only restriction for choosing coffee plants was to include plants at different distances from the trees, including distances up to three times the radius of the tree crowns or half-way to the next tree.

Table 5-1. Criteria for tree and site selection for transect studies on commercial farms.

The sites needed to have:
1. Widely spaced trees separated by gaps wider than individual tree crown diameters.
2. Similar soils to avoid or minimize soil by tree-species interactions (the goal was to compare species effects and not soil effects).
3. Soils of high nutrient status from natural high fertility and/or fertilization. It was assumed that this would minimize tree-coffee competition for nutrients relative to the importance of shade.
4. Homogeneous soil around the trees to assure similar (original) edaphic conditions for all coffee plants in the transect.
5. A population of coffee plants that is as homogeneous as possible in age, size, vigor and production. This reduces the number of plants needed for each plot.
6. Similar management of all coffee plants along the transect.
7. Collaborative and dependable farmers to facilitate future evaluations.

The sample size was restricted by the number of similarly-aged coffee plants around each tree that were not in the AI of any adjacent tree. Increasing the numbers around each tree would have forced to include unrepresentative coffee bushes such as replants. This would have compromised the data interpretation by incorporating a distance X plant age interaction.

Coffee Management

Since the plots were selected in different commercial plantations, the coffee management may have differed among sites. To limit such differences, all sites were on large plantations that are typically managed relatively close to the agronomic recommendations of the Coffee Institute of Costa Rica (ICAFE). Typical recommendations consist of moderate to high mineral fertilization and two to three applications per year of micronutrients and fungicides (for details see Chapter 3). Since also the soils were of similar characteristics, all of volcanic origin (cf. Chapter 2), the differences in environmental conditions (except for the stronger dry season at the "San José" site) and coffee management were assumed to be relatively small. Selecting the plots from large farms increased the likelihood that, overall, all the coffee plants received the same agronomic

treatments as their neighbors, since the management of large coffee fields consists typically of blanket applications.

Parameters and Statistics

The following parameters were assessed for each coffee plant (for details on methodology see Chapter 3): basal diameter, plant height, crown diameter, and plant foliation. Coffee production was assessed as the number of fruits on each plant before the first harvest (cf. Chapter 3). This number equals the potential production of the plant in a given year if all the fruits develop to full maturity. The number of flowering buds was assessed in a similar way, assuming that the number of flower buds at the time of the assessment was proportional to the cumulative number of flowers that opened during the following season.

Foliar and fruit infection was evaluated for *Cercospora coffeicola* ("Chasparria"), *Hemileia vastatrix* ("Roya" = leaf rust), *Mycena citricolor* ("Ojo de gallo") and *Colletotrichum* spp. ("Antracnosis"). Infection level was quantified for each plant as a visual estimate of the percentage of leaves or fruits infected on more than 5% of their surface (one-sided for leaves). Since the objective was to compare the infection of whole plants on a relative scale, this estimate was preferred over the infected-leaf-count method applied at the branch level described by Von Chong and Bonilla (1990)

and Monterroso and Calderón (1995). Other advantages were that the assessments were non-destructive and faster. To correct for time-induced biases towards over- or underestimates, all plants at each site were evaluated in one session, and groups of plants close and far from the trees were evaluated alternately. Distances between coffee plants and trees were measured to the closest decimeter.

Results

The following sections present the transects for the individual trees of the five tree species. Since the transects were not replicated in this pilot study, the inferences from the regression are restricted to the individual trees sampled. The description of coffee attributes under the trees of each species consists of a section on potential fruit production and flowering and another on the vegetative condition and disease load of the coffee plants.

Coffee under *Casuarina equisetifolia*

Production and flowering

Both potential production and flowering were only loosely correlated with distance from the tree stem. The number of fruits and flowers at > 5 m distance increased slightly (Figure 5-2). Following Figure 5-1, these patterns

suggest a neutral to slightly negative compatibility with coffee for this tree of *Casuarina*.

Vegetative condition

Neither plant height nor crown diameter differed with distance from the tree (Figure 5-3A). However, the plants closest to the tree stem retained significantly more foliation. Despite the large variability associated with leaf infection, there was a significant trend towards higher infection closer to the tree (Figure 5-3B). Fruit infection did not show a consistent trend with distance (Figure 5-3C).

Coffee under *Cassia grandis*

The tree selected was reported to be 50 to 60 years old. It had a crown diameter of 15 m, the base of the crown was at 5 m and the total tree height was 14 m.

Production and flowering

Potential fruit production was not affected clearly by distance to the tree ($p = 0.95$ for linear regression). While the coffee plants at < 5 m from the tree stem were on average slightly less productive than those at 5 m to 10 m, most of the lowest-productive bushes were found outside the AI of the tree, i.e. at > 20 m (Figure 5-4A). The number of flowers increased slightly ($p = 0.11$) towards the tree, but the correlation was weak (Figure 5-4B).

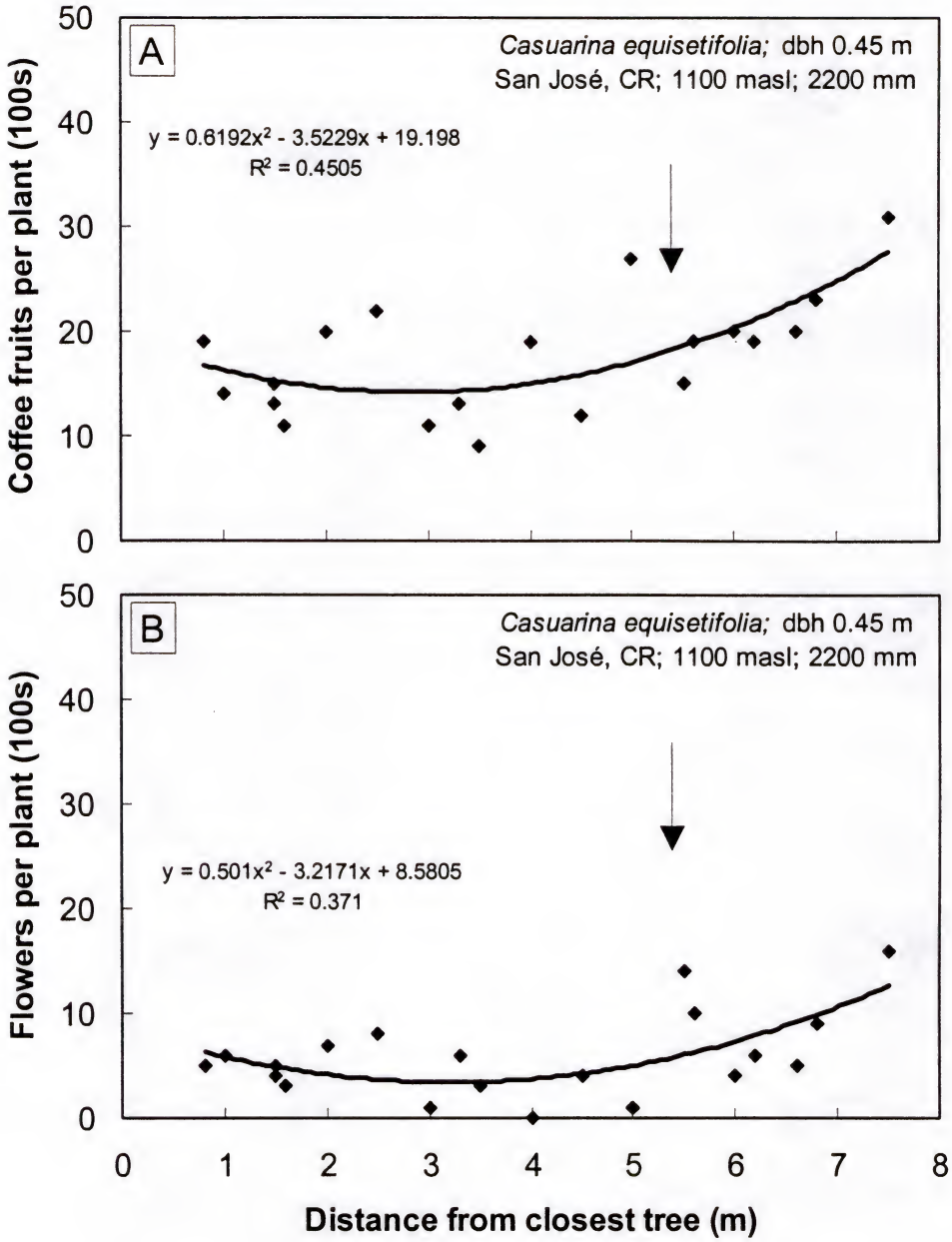


Figure 5-2. (A) Number of fruits (= potential production; p = 0.006; n = 20) and (B) number of flowers (p = 0.02) per coffee plant as a function of distance from the stem of an individual tree of *Casuarina equisetifolia*. The arrows mark the crown edge of the tree.

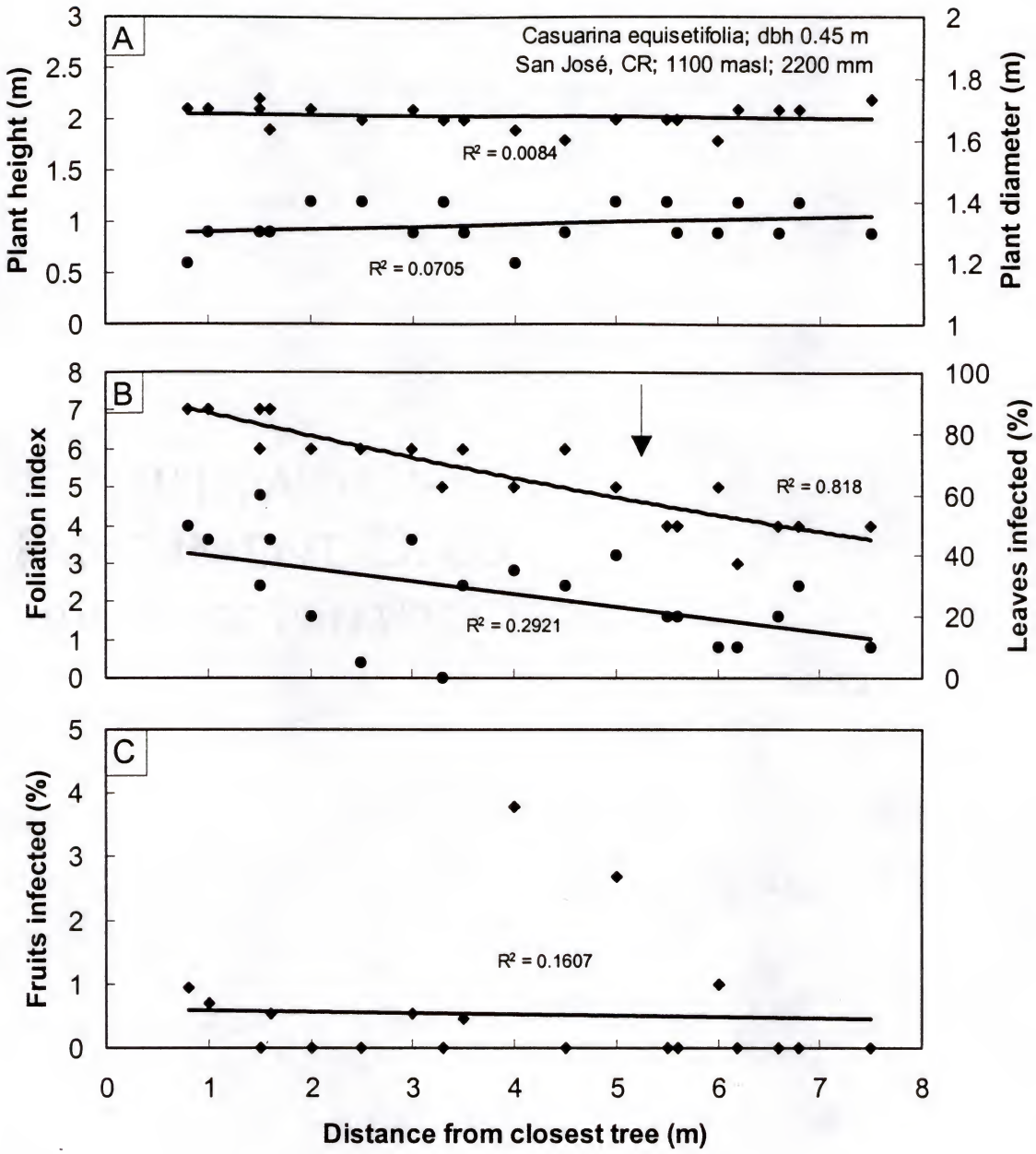


Figure 5-3. Vegetative attributes of coffee plants as a function of distance from the stem of an individual tree of *Casuarina equisetifolia*: (A) plant height ($p = 0.70$) and diameter ($p = 0.26$), (B) foliation index ($p = 0.0001$) and leaf infection ($p = 0.0001$), and (C) fruit infection ($p = 0.86$). The arrow marks the crown edge. Diamond symbols refer to the left y-axis, circles to the right.

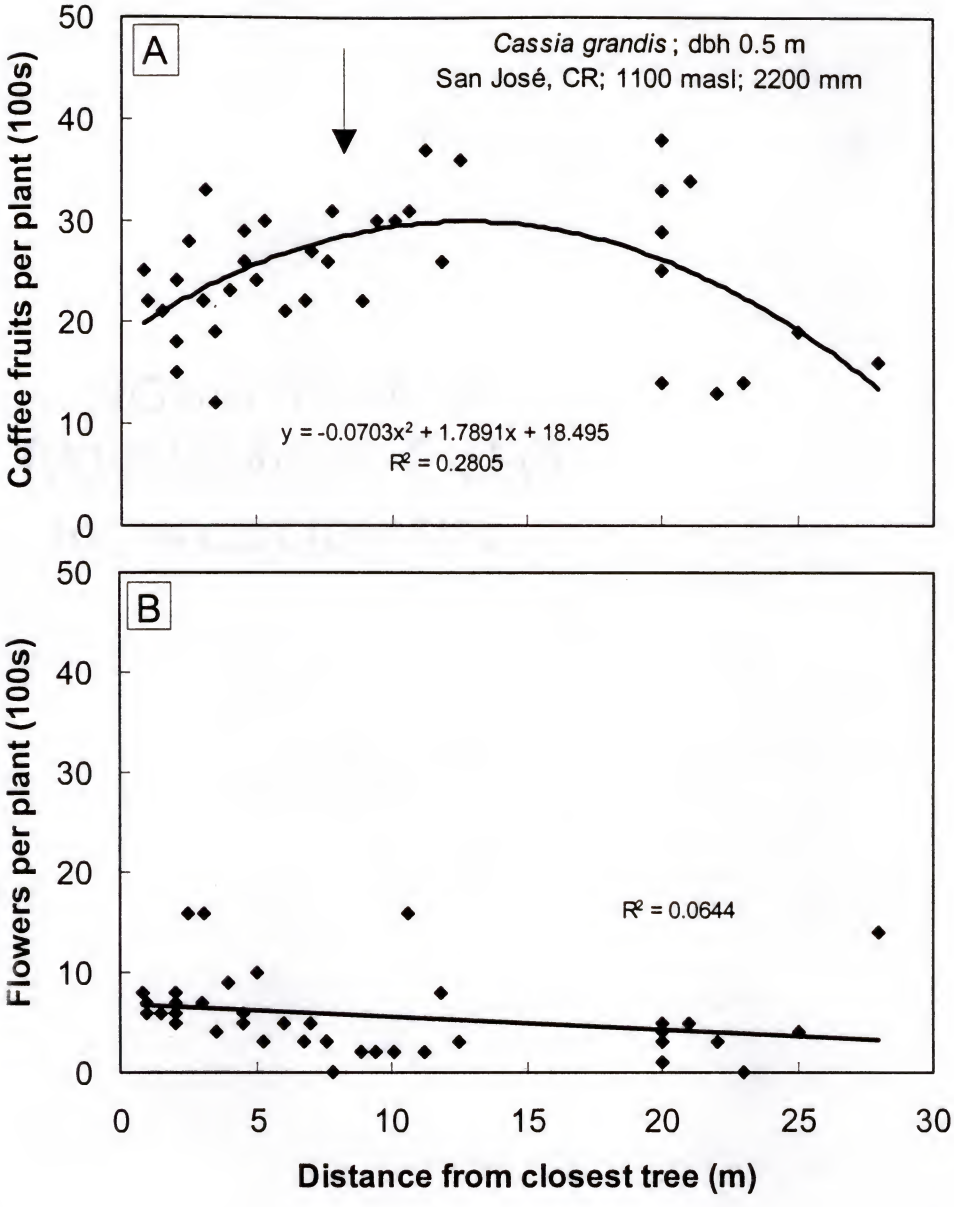


Figure 5-4. (A) Number of fruits (= potential production; p = 0.002; n = 40) and (B) flowers (p = 0.11) per coffee plant as a function of distance from the stem of an individual tree of *Cassia grandis*. The arrow marks the crown edge of the tree.

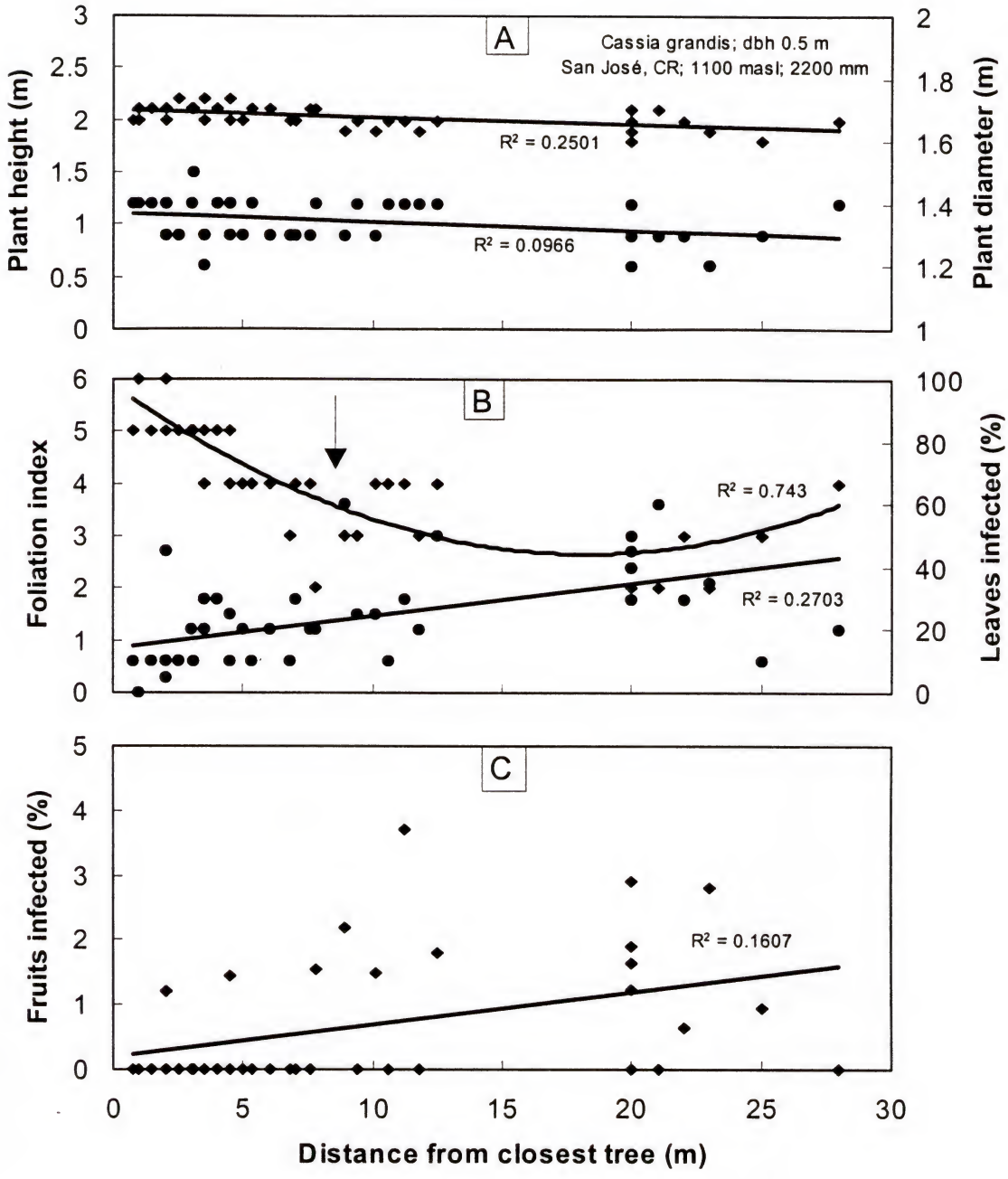


Figure 5-5. Vegetative attributes of coffee plants as a function of distance from the stem of an individual tree of *Cassia grandis*: (A) plant height (p = 0.001) and diameter (p = 0.05), (B) foliation index (p = 0.0001) and leaf infection (p = 0.006), and (C) fruit infection (p = 0.01). The arrow marks the crown edge. Diamond symbols refer to the left y-axis, circles to the right.

Vegetative condition

Height, diameter, and the foliation index of coffee bushes increased significantly towards the tree stem (Figure 5-5). Plants outside the AI of the tree, i.e. at > 20 m, retained less then 40% of their maximum foliage. Leaf infection (Figure 5-5B), dominated by coffee leaf rust (*Hemileia vastatrix*), and fruit infection (Figure 5-5C) increased outside the AI.

Coffee under *Citrus aurantium*

The selected tree was 8 m tall with a crown diameter of 6 m and a crown base height of 3.5 m.

Production and flowering

While the number of fruits of coffee bushes decreased significantly towards the tree stem, flowering was not affected (Figure 5-6). The plant-to-plant variability of the number of flowers was very large at any distance.

Vegetative condition

Coffee bushes closest to the tree were significantly smaller (Figure 5-7A). Although the foliation of coffee bushes was very heterogeneous, it increased towards the tree (Figure 5-7B). There were no infected leaves. However, fruit infection increased significantly with increasing distance from the tree stem (Figure 5-7C).

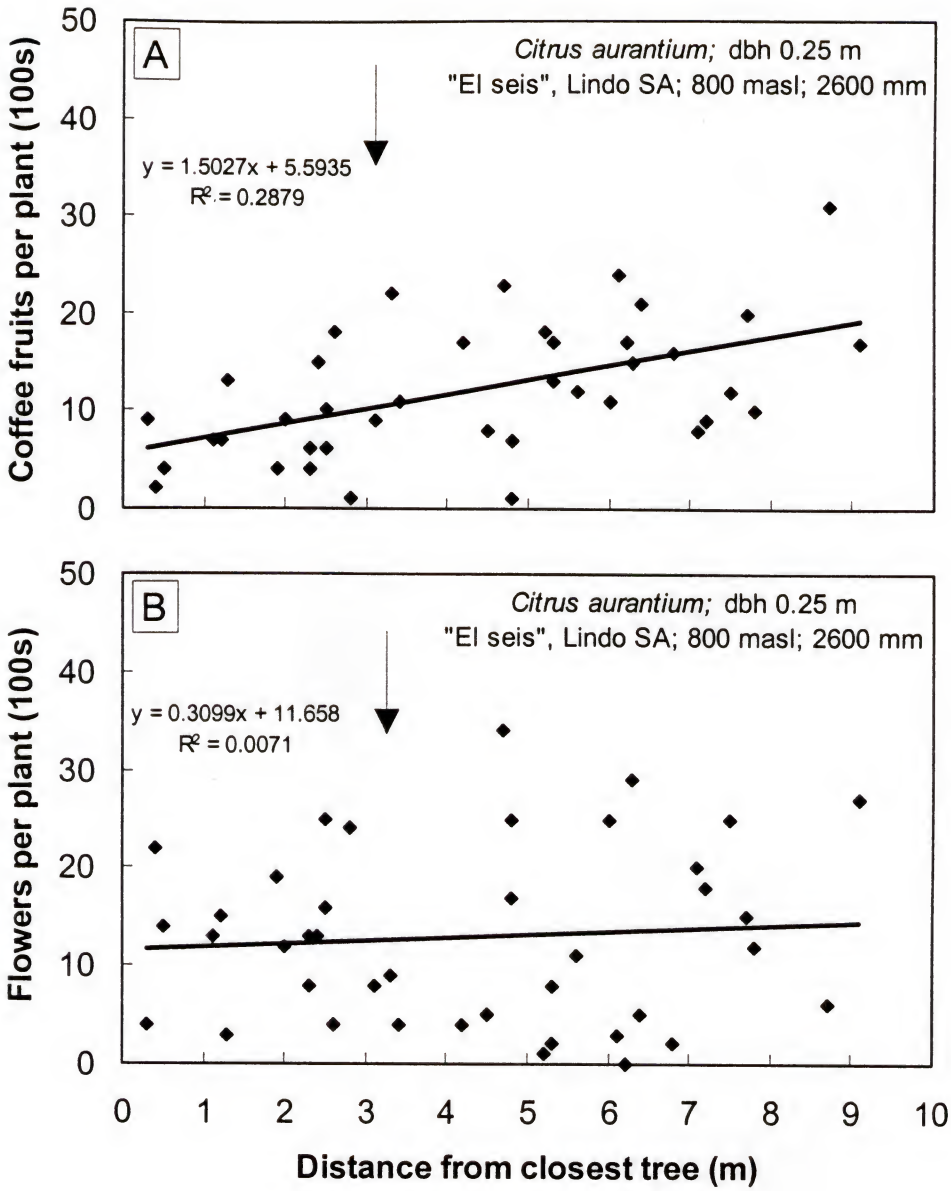


Figure 5-6. (A) Number of fruits (= potential production; p = 0.0004; n = 40) and (B) flowers (p = 0.61) per coffee plant as a function of distance from the stem of an individual tree of *Citrus aurantium*. The arrow marks the crown edge of the tree.

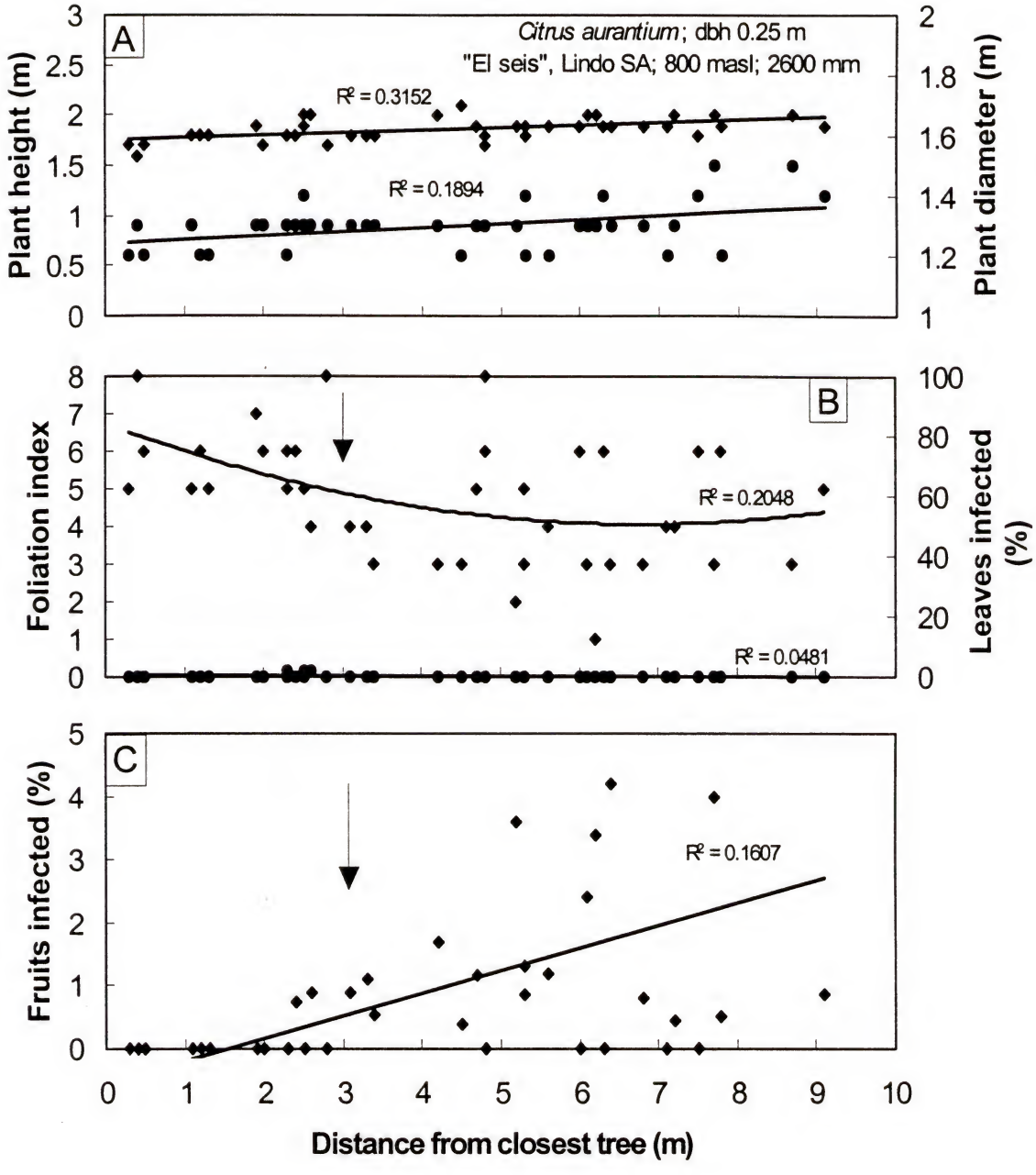


Figure 5-7. Vegetative attributes of coffee plants as a function of distance from the stem of an individual tree of *Citrus aurantium*: (A) plant height ($p = 0.0002$) and diameter ($p = 0.005$), (B) foliation index ($p = 0.014$) and leaf infection ($p = 0.17$), and (C) fruit infection ($p = 0.001$). The arrow marks the crown edge. Diamond symbols refer to the left y-axis, circles to the right.

Coffee under *Croton killipianus*

Since *Croton* was planted on a field boundary as a linear windbreak, the transects were laid perpendicular to the tree row. The selected trees, planted at 0.9 m distance between them, were five to seven years old. Each Croton plant had two to six individual stems, each with a diameter at breast height (dbh) of 7 cm to 10 cm. The tree crowns had a diameter and height of 8 m and 6 m, respectively. The base of the tree crowns was at 2 m above ground.

Production and flowering

Both the numbers of coffee fruits and flowers per plant were strongly reduced close to the trees (Figure 5-8). The reduction of flowering was even stronger than that of fruit production. While reduced fruit production was limited to coffee bushes within the crown area of the trees, i.e. up to about 4 m from the trees, flowering was strongly reduced even up to 7 m from the trees (Figure 5-8).

Vegetative condition

The crown diameter of coffee bushes was significantly smaller ($p = 0.02$) closer to the trees. The effects of distance to the closest tree on plant height, foliation and infection of leaves and fruits were not significant (Figure 5-9).

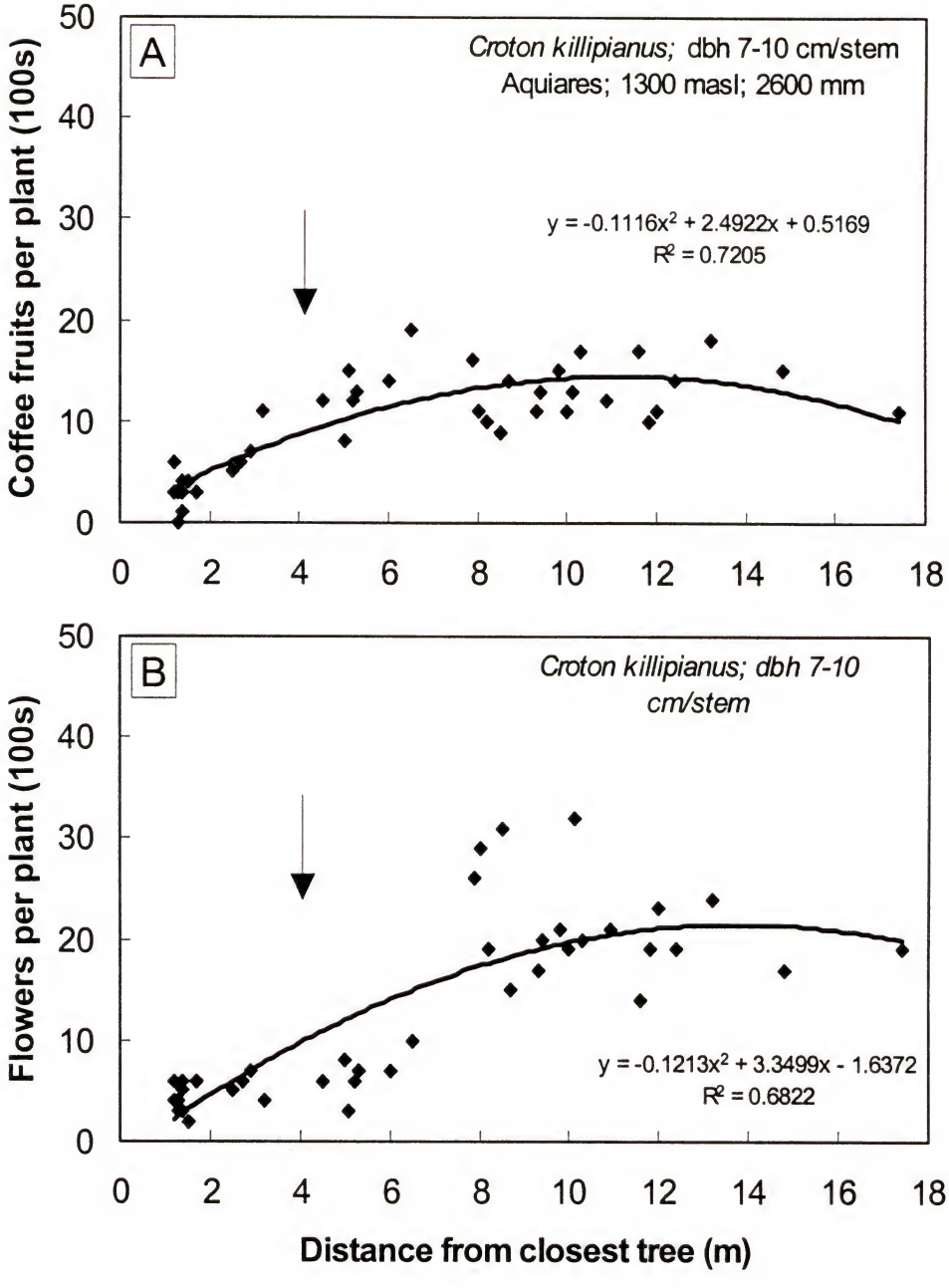


Figure 5-8. (A) Number of fruits (= potential production; p = 0.0001), and (B) flowers (p = 0.0001) per coffee plant as a function of distance from the stems of a windbreak of *Croton killipianus*. The arrow marks the crown edge of the tree.

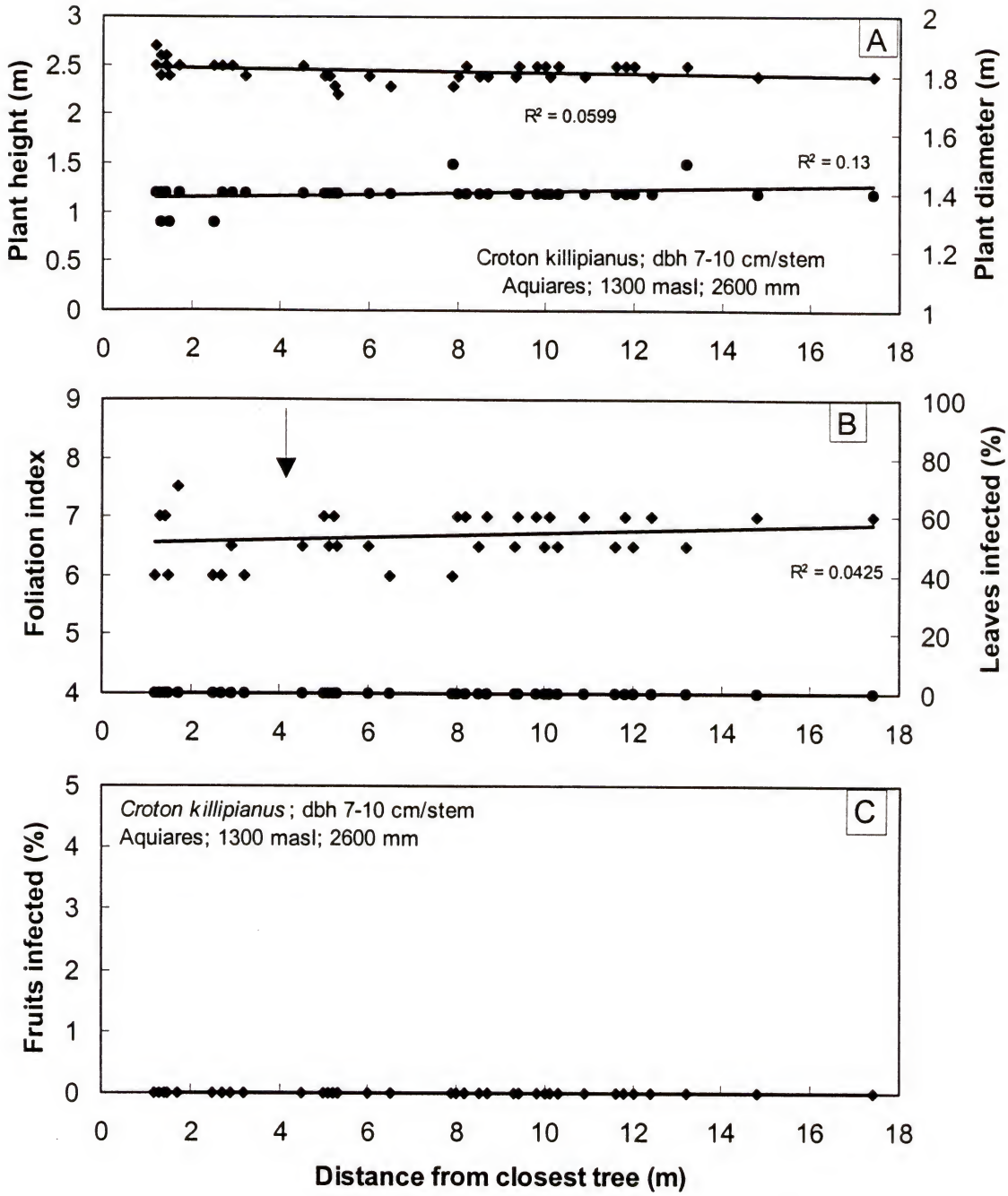


Figure 5-9. Vegetative attributes of coffee plants as a function of distance from stems of a windbreak of *Croton killipianus*: (A) plant height (p = 0.13) and diameter (p = 0.02), (B) foliation index (p = 0.20) and leaf infection, and (C) fruit infection. The arrow marks the crown edge. Diamond symbols refer to the left y-axis, circles to the right.

Coffee under *Eucalyptus deglupta*

For this species, three similarly-sized trees were randomly chosen for the transects and the coffee data were pooled for the three trees. Total tree height ranged from 12 m to 14 m. Crown height and diameter ranged from 7 m to 10 m. The height of the crown bases was at 5 m to 6 m.

Production and flowering

Both fruit production and flowering tended to be slightly reduced close to the trees (Figure 5-10). However, both correlations were weak, and the plant-to-plant variability in the number of flowers per plant was very high (Figure 5-10B).

Vegetative condition

The effects of distance on plant dimensions, foliation and infection of leaves and fruits were not significant (Figure 5-11). This indicated a relatively homogeneous microclimatic pattern that did not differ enough under the open crowns of *Eucalyptus deglupta* to cause a morphogenetic response or locally higher infection of the leaves or fruits.

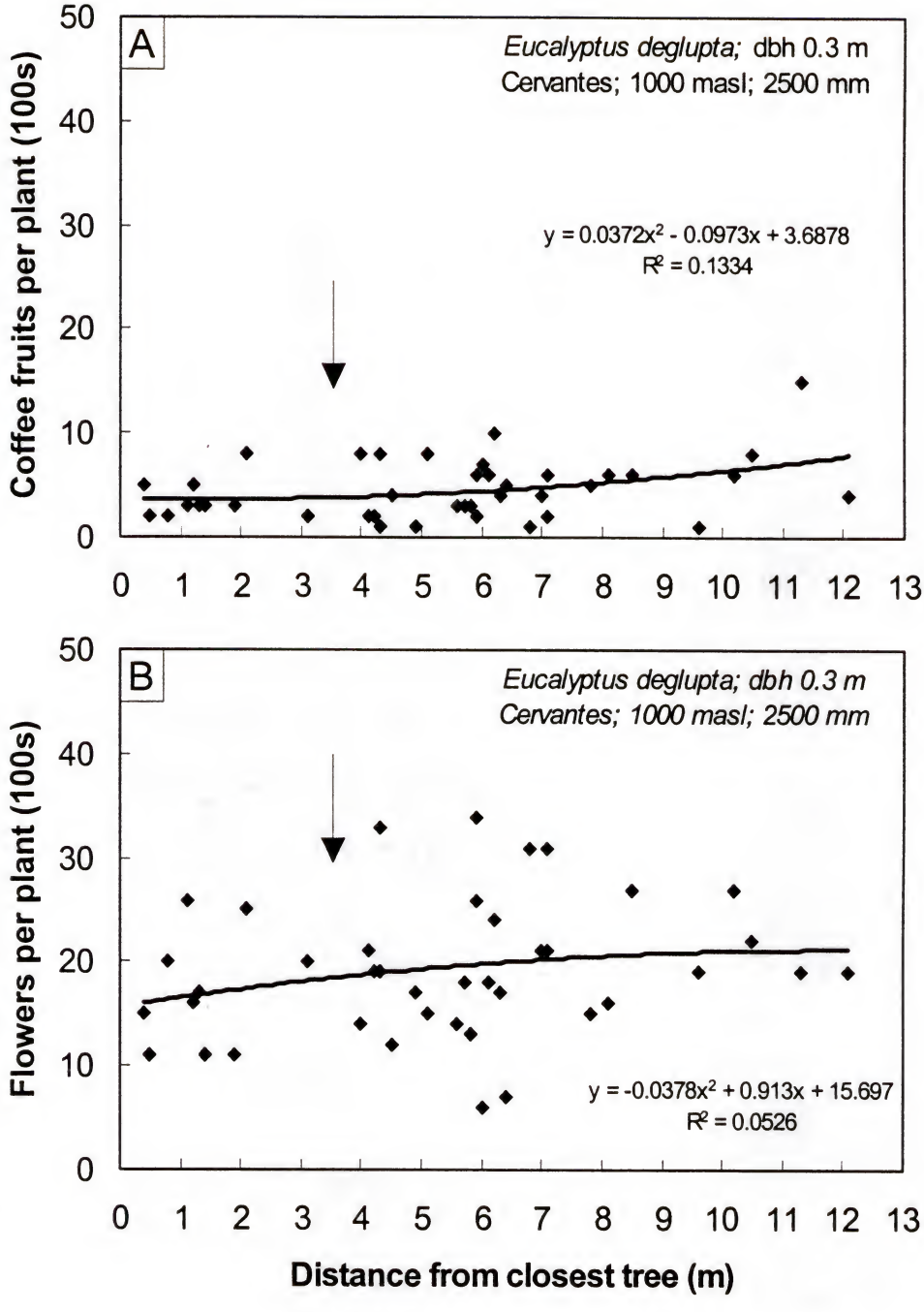


Figure 5-10. (A) Number of fruits (= potential production; p = 0.07; n = 40) and (B) flowers (p = 0.36) per coffee plant as a function of distance from three similarly-sized trees of *Eucalyptus deglupta*. The arrows mark the crown edges of the trees.

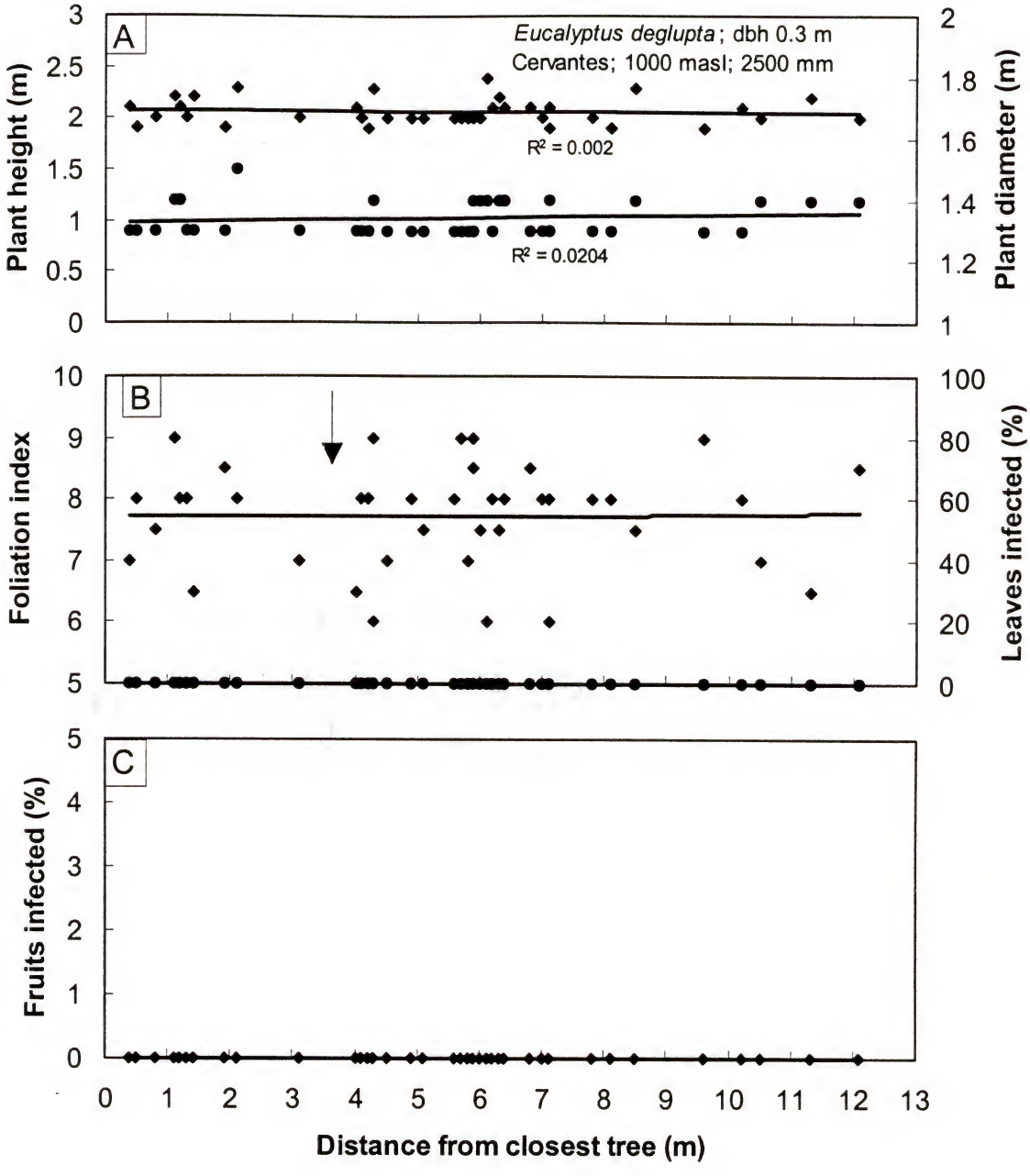


Figure 5-11. Vegetative attributes of coffee plants as a function of distance from three similar-sized trees of *Eucalyptus deglupta*: (A) plant height ($p = 0.79$; $n = 40$) and diameter ($p = 0.38$), (B) foliation index ($p = 0.93$) and leaf infection, and (C) fruit infection. The arrow marks the crown edges. Diamond symbols refer to the left y-axis, circles to the right.

Discussion

Tree Compatibility

For the following discussion, tree-compatibility refers to ecological compatibility evaluated by biophysical attributes of coffee plants. In order to compare the effects of the individual trees studied, I codified the trees' effects on the different coffee attributes as positive (+), neutral (0) or negative (-)(Table 5-2). Neutral effects with a tendency towards positive or negative were coded as "0-" or "0+".

The overall effects of the trees studied on coffee attributes (Table 5-2) suggest the following ranking in the order from most to least compatible: *Cassia grandis* > *Casuarina equisetifolia* = *Eucalyptus deglupta* > *Citrus aurantium* = *Croton killipianus*. This ranking separates the species into three groups, highly, intermediate and poorly compatible. The wide-crowned leguminous *Cassia grandis* showed most beneficial effects of all species. Its deciduousness during the dry season may have contributed to this. For the coffee plants underneath, the flowering stimulus of increased light under a leafless tree canopy might have been strong enough to compensate for the

Table 5-2. Comparison of tree effects on coffee. The attributes of coffee plants under the tree crown are better (+), equal (0) or worse (-) than outside of the tree crown (based on transect sampling).

Attribute	C.g.[1]	C.e.[2]	E.d.[3]	C.a.[4]	C.k.[5]
Fruiting	0+	0-	0-	-	-
Flowering	+	0-	0-	0-	--
Plant height	+	0	0	0-	0
Plant diameter	+	0	0	0-	0
Foliar index	++	+	0	+	0
Leaf infection[&]	+	-	0	0	0
Fruit infection[&]	+	0	0	+	0

[1] *Cassia grandis*
[2] *Casuarina equisetifolia*
[3] *Eucalyptus deglupta*
[4] *Citrus aurantium*
[5] *Croton killipianus*
[&] a positive effect means reduced infection

potentially negative effects of loss of shade during the dry season (Rodriguez 1935). Furthermore, when *Cassia grandis* is in full leaf, both the natural small gaps in the spread-out canopy and the relatively fine composite leaves permit moderate light penetration in the form of a "dappled" shade. This type of shade was described as desirable for coffee production by various authors (e.g., Lock 1888; Cook 1901; Alvarado 1935; Willey 1975). The positive results under the homogeneous yet "open" canopy of the selectively pruned *Erythrina poeppigiana* (Chapter 3; "open shade"), creating a similar shade pattern, supports this notion. Recent photosynthetic studies provide a possible explanation. Besides the benefits to photosynthesis of moderate temperatures under such shade (Jones 1992), photosynthesis might also benefit from the short direct sun exposure as sunflecks pass over plant leaves. During short sunflecks, post-illumination carbon fixation may increase measured carbon gain substantially over the predicted values (Chazdon 1988). It remains to be validated, however, to what extent this may benefit coffee production or vigor.

The significantly higher leaf retention coupled with lower leaf infection close to the tree (Figure 5-5B) demonstrated the higher plant vigor under the AI of *Cassia*. Therefore, the observations on *Cassia* support the arguments

in favor of leguminous trees for shade (Budowski et al. 1984; Beer et al. 1998).

The tendency towards reduced production and flowering under the tree of *Casuarina* studied confirms farmers' statements claiming low compatibility of *Casuarina* with coffee. However, the trend was weak and should not be over-interpreted due to the limited number of coffee plants that could be sampled because of the proximity of neighbor trees. This low number of coffee plants limits the interpretation of this one-time assessment. The lack of an effect of distance to the tree on coffee dimensions reflects the relatively "open" tree crown which did not alter the light environment underneath enough to cause a photomorphogenetic response (Larcher 1980) in the coffee plants. However, it was surprising to find the plants close to *Casuarina* producing more fruits than expected according to farmers' accounts. This apparent discrepancy could reflect a tree effect X environment interaction: while *Casuarina*'s open crowns and erect habit permits adequate light penetration under any environmental condition (including the one studied), its below-ground competitiveness (and hence an overall negative effect of the tree) might be stronger under conditions of stronger nutrient or water-limitations (Wilson 1988; Casper and Jackson 1997) than at the site studied. The

absence of strong water or nutrient stress may have limited the potential negative effects of *Casuarina* on coffee at the study site. This might also have been the case for reportedly successful associations of *Casuarina* with coffee in Papua New Guinea (Bourke 1985) and other crops in Australia (Thiagalingam 1983). The higher leaf retention closer to the *Casuarina* tree may have resulted from the moderate shading by the tree which alleviated heat stress at a time when both solar insulation and plant exhaustion (from a full load of berries prior to harvest) were at their maximum (beginning of the dry season). If confirmed in other studies with more plants, the higher foliar infection under the tree crown (Figure 5-3B) deserves attention.

The reduced production of coffee bushes close to the selected tree of *Citrus* was probably primarily due to the dense crown casting a heavy shade. Although many species of *Citrus* are known to have a dense lateral root system in the upper soil horizons (Castle 1987), the high levels of fertilization on the deep volcanic soil most likely limited the importance of below-ground competition relative to that of shading (Wilson 1988; Callaway and Walker 1997). The production-distance pattern described for *Citrus* (Figure 5-6) is typical of a species of low compatibility. The observation that flowering under *Citrus aurantium* was not

affected by distance might be the result of the relatively small crown diameter of the tree. This feature may have permitted the sun to reach most of the coffee bushes underneath at different times of the day, thus stimulating flowering even of plants that were relatively close to the tree. Higher leaf retention in the AI of *Citrus* may have resulted from reduced heat stress under the shade of *Citrus*. The higher fruit infection outside the AI may have been due to the increased susceptibility of stressed plants there.

The strong reductions of flowering and fruiting under *Croton killipianus* were probably attributable primarily to the dense crowns casting a heavy shade. Although root competition could potentially play an important role, the high water and nutrient availabilities render it most likely less important than shading (Wilson 1988; Callaway and Walker 1997). This production-distance pattern, even more pronounced than for *Citrus*, is typical of a species of low compatibility. The absence of differences in foliation indices or infection levels points to the climatically ideal conditions for coffee at 1300 m a.s.l. At this elevation, in the optimum range for *Coffea arabica*, plants have their highest vigor which reduces susceptibility to pests and diseases (Rodriguez 1935; Agrios 1988; Wrigley 1988).

Furthermore, some pathogens are less aggressive at lower temperatures.

The weak correlations of distance between coffee bushes and trees with production and flowering of *Eucalyptus deglupta*, similar to those under *Casuarina*, indicate an intermediate interaction between the *Eucalyptus* trees studied and the coffee. Again, the high nutrient and water availability at the study site might have limited below-ground competition for these resources (Casper and Jackson 1997), and the open crown of *Eucalyptus deglupta* permitted adequate light penetration. This might explain why there was only a relatively weak response to distance to *Eucalyptus*.

Sampling and Sample Size Considerations

The character of one-time and one-site evaluations of coffee parameters under only a few individual trees used for this exploratory study imposed three main limitations. First, one-time assessments do not permit to characterize the dynamics of coffee vigor or disease development. It would be desirable to establish permanent transect plots where the same plants can be revisited periodically. When such repeated observations are not possible, one-time evaluations should be made at a time of maximum stress for the plants, as in the present study. Maintaining high plant vigor, an important determinant for plant resistance to

disease infection (Thurston 1992; Chaverri and Alvarado 1996) is most critical for coffee plants at times of maximum photosynthate demand during seed filling (Wrigley 1988).

The second limitation regarding sampling was that the studies used only one site per tree species. While I attempted to minimize the importance of the species X site interactions by restricting the variation in soil and climatic parameters, these interactions should ideally be evaluated over the whole ecological range of the species of interest. Studying the same species in contrasting environments would provide clues as to the importance of different environmental factors that determine the outcome of the tree-coffee interaction. For example, it would be important to test the hypothesis that *Eucalyptus deglupta* can be compatible with coffee only in the absence of water and nutrient limitations, but not on nutrient poor soils or dry sites.

The third main limitation to the study was the low number of coffee plants and trees evaluated. While it was desirable to include as many coffee plants as possible, the actual number of plants that could be evaluated was limited by the requirements of homogeneity (cf. Table 5-1), as was the case for *Casuarina equisetifolia*, or by the time required for the evaluation. The best way to increase the

number of plants to be evaluated might be by making transects around many trees of each species in each ecozone, and repeating this in different ecozones. The transects around each tree would then serve as replicates to detect abnormalities of data around specific trees and to generalize the information from the individual-tree level to the species-level.

Limitations of the Transect Approach

While being fast and versatile for generating farmer-relevant information on tree-crop interactions, the transect approach used here is subject to several limitations. First, it cannot provide direct information about the mechanisms responsible for the effects. The effects of, e.g., shading, belowground competition, and allelopathy emerge only as a mixed effect. However, replicating the transects along environmental gradients could provide important clues about the possible mechanisms involved (Callaway and Walker 1997; Holmgren et al. 1997), although a clear separation of mechanisms, particularly of allelopathy from resource competition, may not be possible at all under natural conditions (Inderjit and del Moral 1997).

A second limitation of the transect approach is that the effects described may be confounded with carry-over effects of previous years or heterogeneous coffee

management, such as variable herbicide applications around different plants. However, prudent choice of sites that meet basic requirements of homogeneity (Table 5-1), monitoring of possible management differences and repeated evaluations of the same sites along environmental gradients can help to overcome these limitations and capitalize on the potential of this simple approach.

Potential of the Transect Approach

The main advantages of the transect approach are due to its low requirements of time, space and money. The approach is very fast since no time is required for planting and long-term management of coffee plantations with different tree species. The evaluations themselves take relatively little time. A transect with about 100 coffee plants can typically be done in less than a day, depending on routine and detail of data collection.

It is also a versatile approach to evaluate a large number of species at different sites. If the sites are located along environmental gradients of, e.g., nutrient or water availability or elevation, then multi-location comparisons of the same species can provide important clues about the underlying mechanisms responsible for the overall effects evaluated. Also, establishing permanent transects for repeated observations would permit manipulation of

nutrient or water content in the AI of the tree in order to elucidate the mechanisms of the tree-coffee interaction.

CHAPTER 6
SCREENING AND MANAGEMENT OF TREES FOR COFFEE

This chapter interprets the results from Chapters 3 to 5 in terms of their implications for the screening and management of tree species that are compatible with coffee. It concludes with a graphical hypothesis to explain tree benefits as a function of two key environmental parameters: elevation and soil fertility.

Based on the shade benefits presented in Chapters 3 and 4, tree management for coffee under suboptimal conditions should aim at homogeneous intermediate shading, centered on 40% shade (Figure 3-13), with fluctuations in shade intensity over the course of the year no larger than those of the "open shade" treatment (about ± 20%; Fig 3-3). This shade pattern would avoid excessive heat stress to unshaded coffee and abrupt microclimatic changes under pollarding on the one hand, and excessive shading on the other. The canopy giving this shade should be separated from the coffee canopy by at least one meter to permit adequate aeration important for the control of fungal diseases (Wrigley 1988). There are two ways to achieve the described shade pattern and canopy

separation. First, tree species can be selected as coffee associates based on their ecological compatibility with coffee (which includes having a crown architecture and phenology that permits the desired shade pattern). And, second, the choice of tree spacing and pruning intensity can adjust the shade pattern to the levels desired.

Tree Species Selection

Assessing and broadening the spectrum of shade tree species and the different management options (fertilization, pruning, thinning etc.) at hand will help to increase or maintain the production of the system, while reconciling the production of an export crop with the production of timber, fruits, and ecological services for a local or regional market (Beer et al. 1998).

While excessive shading of leguminous trees such as *Erythrina* spp. or *Inga* spp. can be adjusted through pruning with relative ease, this is less feasible with fruit trees and timber trees. Thus studies on shading patterns and phenology of timber and fruit tree species deserve special attention. The phenological studies on *Erythrina poeppigiana* (Borchert 1980) and tree species from lowland forests

(Frankie et al. 1974; Newstrom et al. 1994) give a useful framework.

In particular, information on the compatibility of tree species with coffee is needed. A highly compatible tree species would have a crown architecture that gives the optimum level of shade for the local conditions, competes little for water and nutrients, and that produces high-value products and ecological benefits quickly. The transect-based methodology to evaluate tree-coffee interactions (Chapter 5) may help to rapidly screen tree species for their compatibility with coffee.

Management of *Erythrina* for Shading Coffee

This section presents management recommendations for *Erythrina poeppigiana* to provide the shade pattern (Chapter 3) that was found to be most beneficial for coffee in the suboptimal environment studied. Given that the intermediate homogeneous shade treatments "open shade" and "shadecloth" produced equal amounts of coffee as the sun or pollarding treatments, while at the same time maintaining the coffee in a better vegetative condition and suppressing weeds (Chapter 3), I recommend a pruning regime which results in this type of shade.

With *Erythrina poeppigiana*, under the site conditions studied, there are two ways to achieve this desired shade pattern and the separation of the tree and coffee canopies mentioned above. First, all trees can be retained at six to eight m spacing, the typical spacing in coffee fields around Turrialba, and pruning of every third to every second branch of the crown can reduce shading whenever it exceeds 70% shade. Two or three branches could be left unpruned so that they can reach maturity and, consequently, shed their leaves during the flowering of the tree which typically coincides with the flowering of coffee (typically between January and March).

Those branches earmarked for pruning, usually carrying dense clusters of foliage in the lower part of the crown, should be pruned at two to three m above the tree's crown base, equivalent to about four to five m above the ground. This assures that at least one m distance will separate the dense clusters of foliage on juvenile resprouts from the coffee canopy. The gaps from the removed branches will permit direct light to filter through the tree canopy. Typically, two to three prunings will be enough in the first two to three years of tree crown growth. Thereafter, pruning frequency can be reduced because the tall branches left

without pruning will have reached maturity with consequent loss of basal leaves and an increasing amount of gaps in the crown (pers. obs. around Turrialba). Where possible, the pruning should not only leave two to three main branches to form a homogeneous canopy with equally distributed gaps from the removed branches, but should also spare some of the lower branches to facilitate tree climbing for later pruning operations. If the pruning is guided by these objectives from early on then the pruning efforts will decrease strongly over time since the tree will retain the basic formation of two to three main branches or stems.

The second way to generate the desired shade pattern and crown base height is through an initial thinning of the tree stand to final distances between trees of 12 to 16 m for *Erythrina poeppigiana* under similar conditions as this study. This thinning generates gaps for light penetration between the trees rather than within their individual crowns and reduces, or eliminates, the need to prune the trees at all (pers. obs.). Once the crowns reach maturity, for *Erythrina poeppigiana* after about three to five years of growth in Turrialba, the trees enter into their mature phenological cycle with partial to complete defoliation during the time of coffee flowering. This phenological

pattern was observed in the third and fourth years of the experiments.

Although endogenous cycles can be important for the phenology of *Erythrina* (Borchert 1980), it appears that the flowering of *Erythrina* often coincides or overlaps with the flowering period of coffee, generally January through March. During this time the increased light penetration through the leafless crowns of the trees can benefit the coffee equally as under pruned or pollarded *Erythrina* trees.

The savings from making weeding operations unnecessary (Chapter 3) and avoiding potential phytotoxic effects of frequent herbicide applications (Bouharmont and Awemo 1993), the increased biodiversity (Perfecto et al. 1996; Greenberg et al. 1997), and the higher quality coffee (Chapter 4) add to the attractiveness of these pruning systems for tall homogeneous shade.

Tree Benefits Increase with Marginality: a Hypothesis

While the literature on the sun-shade discussion is replete with reasons for or against shade (cf. Chapter 1), no general framework has been proposed to unify this information for different environments. In the following section, I propose a unifying graphical hypothesis based on

environmental key factors which determine the benefits of trees for coffee.

For the following discussion, I define shade as an average of 50% of photosynthetically active radiation (PAR) of full sun available for coffee plants under the canopy of the associated trees. When comparing the production of an imaginary (yet typical) shaded versus an unshaded coffee field (shade being the only difference between the two fields) along an elevational gradient, the following pattern is likely: irrespective of soil conditions, a hypothetical relationship between coffee production and elevation, the latter determining microclimatic parameters, would show a maximum of coffee production at "ideal" coffee elevations (typically 1000 to 1300 m a.s.l. in Costa Rica)(Fig 6-1). This would hold equally for both systems.

Looking at soils without major limitations of rooting depth, nutrient or moisture availability (Figure 6-1A), this maximum would be more pronounced for sun-grown coffee than for shade-grown coffee. Outside this optimum elevational range, the production of sun-grown coffee decreases strongly in response to higher temperature stress at low elevations, and low temperature and possibly wind damage at higher elevations. Under these suboptimal conditions, planting

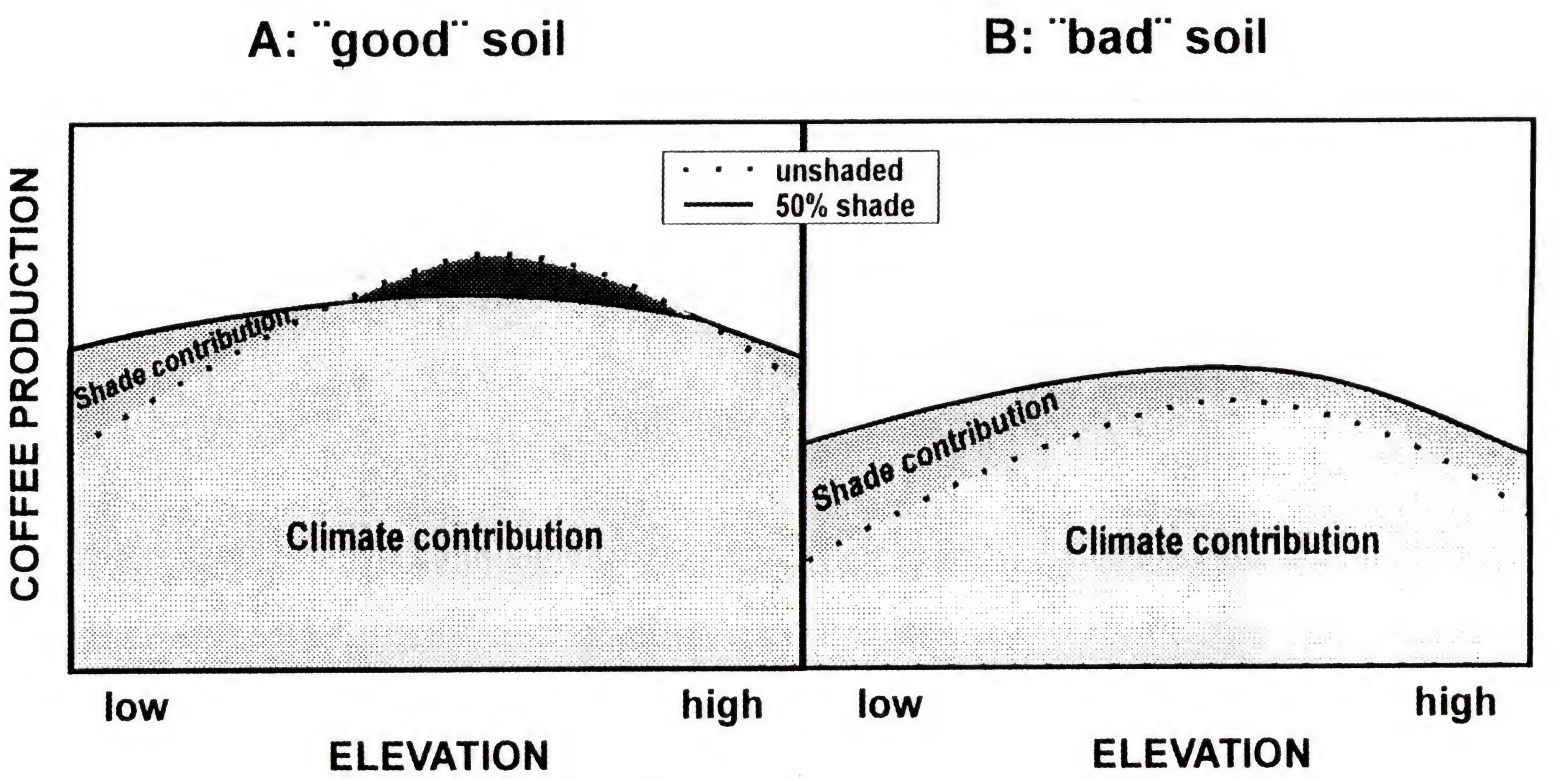


Figure 6-1. Hypothetical coffee production without shade and under trees giving 50% shade as a function of elevation for soils without (A) or with (B) limitations of rooting depth, nutrients, or moisture. While production of unshaded coffee for given soil conditions and elevation depends primarily on climatic conditions ("Climate contribution"), shade may improve production ("Shade contribution") under marginal conditions. At ideal coffee elevations and on soils without limitations shading may reduce production (dark area).

trees amongst coffee to give intermediate shade at lower elevations and to reduce the impact of wind and low temperatures at high elevations (e.g., in the form of a windbreak) can improve production over that of sun-grown coffee as long as tree-crop competition for nutrients or water is not severe. This positive effect of the trees is labeled as "shade contribution" in Fig 6-1.

In contrast, shading of coffee at optimum elevations would result in a yield depression relative to sun-grown coffee (the dark area in Fig 6-1A reflects such "excessive shade"). Compared to these "good" soils, on soils with limitations, the typical situation for many, if not most, coffee areas, production of both sun-grown and shaded coffee would be reduced at all elevations (Fig 6-1B). However, the ecological benefits of associated trees would allow the reduction of the shaded coffee system to be relatively less than that of the sun-exposed system. Consequently, the shade contributions from the trees would increase on such poor soils and would now extend over the whole elevational range of coffee cultivation (Figure 6-1B).

The proposed model accomodates well the shade responses described in this study, i.e. as positive shade contribution in the low-elevation part of Fig 6-1A. Similarly, it

accommodates the results of long-term experiments which were repeated at different elevations in Costa Rica: at another low-elevation coffee plantation in Turrialba, the 8-year harvest average from unfertilized shaded plots exceeded that of sun-plots by 65% (650 m a.s.l.; Ramirez 1993). At higher elevations in Grecia (950 m a.s.l.) and San Isidro (1350 m a.s.l.), reducing the low-elevation temperature stress, this advantage of the shaded plots was still marked but reduced to 37% and 17%, respectively (ICAFE-MAG 1989; ICAFE 1996b). This corresponds to the relative reduction of the "Shade contribution" with increasing elevation in Fig 6-1. Fertilization of both shade and sun plots apparently relieved nutritional limitations and allowed the sun treatment to exceed over the shade treatment at the "ideal" elevation of 1350 m a.s.l. However, in agreement with Fig 6-1, sun plots did not exceed shade at the two lower elevation sites (this study and Ramirez 1993) where the sun treatments were probably more limited by temperature stress than by nutrition.

In conclusion, using soil condition and elevation to separate coffee responses to shading into optimum and suboptimum environments may provide an avenue for reconciling contradictory yield evaluations within one

unified model. However, the good fit for the data from different elevations in Costa Rica needs to be checked against information from other coffee areas of the world.

This model, if confirmed, could help to prioritize tree introductions into coffee fields starting with those where the tree/shade contributions are maximum. In this sense, this model would help to develop "recommendation domains" for the tree-coffee associate, similar to the approach of "Adaptability Analysis" by Hildebrand and Russell (1996).

Under marginal conditions, typical for many coffee farms in Latin America, it is hypothesized that shade alleviates the environmental stress to the coffee plants, thus permitting balanced growth and slower and more homogeneous grain filling and maturation which ultimately would yield a higher-quality product. However, the validity of this hypothesis needs to be tested for other suboptimal zones and checked against a similar comparison from optimal coffee zones.

CHAPTER 7
SUMMARY AND CONCLUSIONS

The results of this study support the hypothesis that trees benefit coffee production in environment that are ecologically suboptimal for *Coffea arabica*. This chapter summarizes the main findings about tree-coffee interactions based on the shade experiments with *Erythrina poeppigiana* (Chapters 3 and 4) and on the transect-based screening of tree species for their compatibility with coffee (Chapter 5). It closes with a summary of suggestions for managing *Erythrina poeppigiana* for optimum shade for coffee (from Chapter 6), and with research recommendations.

Tree-Coffee Interactions

The experiments have shown that, despite high inputs of agrochemicals reported to reduce shade requirements, coffee benefitted strongly from intermediate shade from *Erythrina poeppigiana*. The data suggested that, for the ecologically suboptimal conditions of high heat loads and moisture studied, the trees' moderating effects on microclimatic

extremes were more important than other ecological benefits such as nutrient cycling.

The "open shade" treatment, centered around 60% shade (i.e. 40% of PAR under the unobstructed sun), under a closed canopy of tall (8 to 12 m tree height) *Erythrina poeppigiana* maintained productivity in four consecutive years at similarly high levels as sun-plots or plots where the trees were pollarded three times per year (Chapter 3). At the same time, plants under intermediate shade maintained higher vigor (Chapter 3) and produced larger and healthier fruits of better organoleptic quality compared to the sun or pollarding treatments (Chapter 4). Shading above 80% (during the first two years) reduced production of Caturra by about 37% and that of Catimor 5175 by about 12%, although only the yield reduction of Caturra was statistically significant. Permanent shade of *Erythrina poeppigiana* throughout the year (open and dense shade), combined with the barrier effect of fallen leaves (4 to 4.8 Mg litter per ha, for the open shade and dense shade treatments, respectively), suppressed weeds completely.

In contrast, seasonal shade under pollarded trees and no shade permitted aggressive weed growth reaching a maximum weed biomass of 3.6 Mg ha^{-1} in the sun plots despite three

to four herbicide applications per year. In these treatments, higher maximum temperatures of air, leaves, and soil indicated a higher level of environmental stress for the coffee plants. This stress was reflected also in foliar concentrations of phosphorus and potassium that approached deficiency. Particularly the foliar concentrations of potassium were strongly reduced in sun (1.1% in 12/95 and 1.2% in 11/97) relative to shade (1.4% in 12/95 and 2.0% in 11/97).

Relative to open and dense shade, the sun and pollard treatments showed significantly higher incidences of *Cercospora coffeicola* resulting in partial to complete defoliation and relatively high production losses. No differences were found among treatments for the incidence of *Hemileia vastatrix* and *Mycaena citricolor*.

In the open and dense shade treatments, the phenological cycle of maturing tree crowns (after reaching four years of age) permitted more light than before to penetrate during a period (December to March) when coffee flowering reportedly benefits from additional light. It was surprising that even extreme shading beyond 80% without significant leaf drop of the juvenile tree crowns in the

first two years of the experiments did not suppress flowering (and hence production) as strongly as expected.

Increasing shade intensity from full sun to more than 80% shade increased fruit weight and bean size significantly (Chapter 4). While the large beans (diameter > 17/64ths of an inch, equivalent to 6.7 mm) accounted for 49% and 43% of the coffee from sun-grown plots for Caturra and Catimor 5175, respectively, these proportions increased to 69% and 72% under dense permanent shade. These changes suggested a stronger shade benefit for Catimor 5175 than for Caturra. Since the conversion percentages from fresh-weight coffee fruits to dry-weight green coffee for export were not affected significantly by the treatments, the weight of 100 fresh fruits (W_{100}) might be useful as a valuable and easily measurable descriptor of green bean weight and hence, indirectly, bean size.

A blind tasting experiment showed shade-induced improvement in appearance of green and roasted coffee as well as in acidity and body of the brew. These benefits from shade were consistent between replications and similar for the two varieties examined, Caturra and Catimor 5175. The effect of shade on aroma of the brew was neutral for Caturra and slightly negative for Catimor 5175.

The beneficial effects of shade on coffee quality illustrate the trees' facilitative effects, primarily through reduction of heat stress, which permitted a slower development of larger fruits under shade, whereas the development of sun-grown fruits was limited by the high heat-loads in this low-elevation suboptimal coffee region.

Transects

Based on one-time transect-based evaluations (Chapter 5), correlations of individual-plant flowering, production, vigor and health with distance to the nearest tree suggested high compatibility of coffee with the individual trees studied of *Cassia grandis*, *Casuarina equisetifolia*, and *Eucalyptus deglupta* under conditions without water limitations. In contrast, the trees studied of *Croton killipianus* and *Citrus aurantium* were found to affect coffee performance negatively, at least partly due to excessive shading by their dense canopies. The differences among the tree species in terms of their effects on coffee demonstrate the potential of this transect-based approach to screen tree species for compatibility with coffee. Repeating transects with different individuals of each tree species over several

years, and on different sites, can help overcome limited sample sizes.

Management Recommendations for Erythrina

Intermediate shade of *Erythrina* can be achieved by two ways: first, the crowns of closely spaced trees (6 to 8 m distance) could be selectively pruned whenever the level of shade exceeds 70%, and second, the tree stand could be thinned to final distances of 12 to 16 m. The latter distances are large enough to avoid crown closure before the crowns become less dense as they mature. The second way demands less labor since no pruning is necessary at all. Once the tree crowns reach maturity, typically after three or four years, the coffee plants underneath will benefit from the periods of leaf loss of *Erythrina*, most pronounced during the main flowering period from December to March.

Research Recommendations

Considering the tree benefits documented in this study and the hypothesis that tree facilitation increases with marginality of the biophysical environment for coffee (Chapter 6), the following questions should be addressed by future research:

1. How do different shade tree species affect the long-term ecological sustainability of coffee production systems?

2. In which production environment (ecological and socioeconomic conditions) do the advantages of shade trees outweigh the costs?(gradient studies)

3. How can the compatibility of tree species with coffee be evaluated in on-farm settings?

4. Which tree species are ecologically compatible/beneficial for coffee in different coffee regions of the world?

5. What is the role of trees for organic production of coffee (via reducing external production inputs)?

Approaches to these questions will likely benefit from multilocation comparisons to go beyond site-specific responses. Methods such as "Adaptability Analysis" (Hildebrand and Russell 1996) can greatly help to interpret such information for the farmers and their production environments. Studies along specifically selected environmental gradients of soil fertility and water availability will help generate information about the mechanisms of the tree-crop interactions, and thus, ultimately, the tools for improved management of agroforestry systems with coffee.

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APPENDIX

Coffee production costs per hectare of a conventional farm in Costa Rica (Lindo S.A. 1994-96)

Product prices of 5-5-98 in Camara de Cañeros, Turrialba
Activities, products and quantities used based on unpub. Data of Felix Granados, Finca Lindo S.A. 1995/6

ACTIVITY	PRODUCT	Amount used l-kg-man-day per hectare	Price per sales unit (Colones)	Quantity/ sales unit	Exchange rate (4-98) (Colones/$)	Unit price US-$/l or kg	COST US-$/ha	% of total	SUBTOTAL % total cost	FACTOR
TREE										
pruning by contract for 3 pollardings per ha and yr							50	2.09	2.09	Tree pruning
COFFEE										
Labor for pruning of coffee		11	1800		250		79.2	3.30		
Labor for deshija		9	1800		250		64.8	2.70		
Labor for replanting		2	1800		250		14.4	0.60		
Coffee plants for replanting		80	50		250		16	0.67	7.27	Coffee mgmt
Harvest of 35 fanegas/ha		700	250		250		700	29.20	29.20	Harvest of 35 fan/ha
Fertilization	F.c. 18-5-15-6-2 (NPKMgB)	315	3145	45	250	0.28	88.06	3.67		
	F.c. 20-7-12-3-2 (NPKMgB)	315	3065	45	250	0.27	85.82	3.58		
	NH4NO3	315	3000	45	250	0.27	84	3.50		
	Labor (man-days for 3 appl.	5	1800		250		36	1.50	12.26	Fertilization
Weed control	Paraquat	5	4750	3.5	250	5.43	27.14	1.13		
	Gardoprim (=Terbutilazin)	5	5655	3.5	250	6.46	32.31	1.35		
	WK Penetrante	2.5	3485	3.8	250	3.67	9.17	0.38		
	Goal	2.5	22685	4	250	22.69	56.71	2.37		
	Roundup	2.5	8305	3.8	250	8.74	21.86	0.91		
	Labor (5 appl./year)	10	1800		250		72	3.00	9.14	Herbicides
Fungicides	Atemi	0.75	16190	1	250	64.76	48.57	2.03		
	Cu	0.75	750	0.7	250	4.29	3.21	0.13		
	Metalosato Multiminteral	1.25	12635	3.8	250	13.30	16.63	0.69		
	Matalosato Boro (Casagri)	0.75	4160	1	250	16.64	12.48	0.52		
	Metalosato Zn (Casagri)	0.75	4175	1	250	16.70	12.53	0.52		
	Labor (3 appl. 03/06/09)	3	1800		250		21.6	0.90	4.80	Fungicides
Nematicides	Counter (Terbufos)	22.5	7770	15	250	2.07	46.62	1.94		
	Labor (1 applic./year)	1	1800		250		7.2	0.30	2.25	Nematicides
Fixed costs (crop exhaustion, depreciation etc.), assumed at 33% of total cost (Rojas 1996)							791	33.00	33.00	
TOTAL COST PER HECTARE							**2397.31**		**100.00**	**Total**
Cost/fanega (US$ in 1998, assuming a production/ha of 35 bags of 46-kg)							**68.49**			

* Rojas G, 1996. Modelo de costos de producción de café. ICAFE.

BIOGRAPHICAL SKETCH

Reinhold G. Muschler was born in 1964 in Ansbach, Germany, where he received his "Abitur" from the Gymnasium Carolinum in 1983. After serving in the German Air Force, he studied Geo-ecology at the University of Bayreuth, Germany, specializing in plant ecology, soils and land-use systems in the tropics. Scholarships and grants from the Studienstiftung des Deutschen Volkes, the Fulbright-Commission, the German Academic Exchange Service (DAAD), the Hans-Krüger Foundation, the University of Florida, and the Halpin-Award enabled him to pursue his interests in tropical agroforestry at the University of Florida, Gainesville, U.S.A., and at the Center for Research and Training in Tropical Agriculture (CATIE) in Turrialba, Costa Rica. After his M.S. work on living supports for black pepper in the lowlands of Costa Rica he changed ecozones by moving on to mid-elevation agroforestry systems with coffee which he has studied intensely since 1993. After short-term consultancy assignments he joined the staff of CATIE in 1996 to work on validation and outreach of promising agroforestry systems

with coffee in Central America. In 1997 he developed and taught a new 3-credit graduate course entitled "Organic Agriculture and Agroforestry" at CATIE focusing on agronomic applications of ecological benefits from well-managed plant associations. He intends to continue working in the field of low-input diverse agroforestry systems, especially with coffee and native tree species in Latin America.

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

P.K.R. Nair, Chairman
Professor of Forest
Resources and Conservation

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Henry L. Gholz
Professor of Forest
Resources and Conservation

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Peter E. Hildebrand
Professor of Food and
Resource Economics

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Hugh L. Popenoe
Professor of Soil and Water
Science

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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This dissertation was submitted to the Graduate Faculty of the School of Forest Resources and Conservation in the College of Agriculture and to the Graduate School and was accepted as partial fulfillment of the requirements for the degree of Doctor of Philosophy.

December 1998

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